PHD

Low-Energy Domestic Architecture: The Impact Of Household Behaviour On The Expected Energy Use Of Passive House Dwellings

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LOW-ENERGY DOMESTIC ARCHITECTURE: THE IMPACT OF HOUSEHOLD BEHAVIOUR ON THE EXPECTED ENERGY USE OF PASSIVE HOUSE DWELLINGS

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Abstract

Reduction of carbon emissions is understood to be vital to help mitigate catastrophic climate change. In Europe, 40% of energy use is attributed to the built environment (European Commission, 2010), with a large proportion of this from dwellings. In line other legislation for decarbonisation under the Climate Change Act of 2008, the UK Government has agreed that all new housing will be ‘zero carbon’ from 2016 onwards. From a technical aspect this task is feasible using improved insulation performance, more airtight building techniques, efficient servicing, and renewable energy technologies. In practice however, post-occupancy evaluation studies highlight a discrepancy between design energy use and measured energy performance, with a tendency for real buildings to use more energy than designed and for projects regarded as ‘low energy’ in design to use an equivalent amount of energy as a pre-existing counterpart (Bordass, 2001; Branco, Lachal, Gallinelli, & Weber, 2004; Gill, Tierney, Pegg, & Allan, 2011). This difference between design and use - ‘the design gap’ - is attributed to both the physical ‘hard’ features of the building (form, area, systems) and occupant-driven or ‘soft’ features (ventilation & heating preferences) by a number of studies (Guerra Santin, Itard, & Visscher, 2009; Socolow, 1978).

This body of work begins with a review of the field and state of the art - occupant influence on energy use in a domestic environment. The first contribution to knowledge is in the adapted utilisation of a piece of software by Richardson et al. which stochastically generated electricity use profiles for homes which are shown to be similar to measured energy usage, both in net energy use and in load profiles (Richardson, Thomson, & Infield, 2008). This adapted software was implemented to generate appliance use profiles for a number of dwelling models. These results are then interrogated and a regression model proposed based on a number of dependent variables identified in the input profiles. The theory of planned behaviour is used to underpin a survey in which a number of households are asked to comment on their attitude and behaviour with regards to energy use in the home – the homes in this case being new-build Passivhaus council-housing in Devon. The results of this project form the second aspect of this work’s contribution to knowledge.

Acknowledgements

It has been a winding trail to get this thesis to where it is now, but the way has been paved with support from many along the way: my parents, for their unquestioning faith and care; Jess, without whom I would not have made it to this point; David Coley and Joanne Smith for their supervision, enthusiasm, and ropework.

I would like to thank all of the residents, who allowed me access to their homes and to their time to conduct the interviews. Their frank accounts were highly valued and I hope their openness to discuss experiences will lead to more comfortable housing for everyone. Thanks also to Exeter City Council and Gale & Snowden Architects for allowing me access and support.

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“All models are wrong, but some are useful.”

- George Box

Contributions - Publications, Conferences, & Presentations

Peer Reviewed and Conference Publications

[Main Author, Peer-Reviewed Journal Article] Blight, T. S., & Coley, D. A. (2013). Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. Energy and Buildings, 66, 183–192.

[Main Author, Peer-Reviewed Conference Paper] Blight, T. S., & Coley, D. A. (2012). The Impact of Occupant Behaviour on the Energy Consumption of Low Energy Dwellings. Conference Paper T11-50, COBEE2012, Boulder, USA

[First Author, Conference Paper] Blight, T. S., & Coley, D. A. (2011). Modelling Occupant Behaviour in Passivhaus Buildings: Bridging the Energy Gap. CIBSE Technical Symposium, DeMontfort University, Leicester, UK

[Co-author, Peer-Reviewed Journal Article] Ramallo-González, A. P., Blight, T.S., Coley, D.A. (2015). New optimisation methodology to uncover robust low energy designs that accounts for occupant behaviour or other unknowns. Journal of Building Engineering, 2, 59-68.

[Co-author, Peer-Reviewed Journal Article] Moran, F., Blight, T., Natarajan, S. & Shea, A. (2014). The use of Passive House Planning Package to reduce energy use and CO_2 emissions in historic dwellings. Energy and Buildings, 75, pp. 216-227. doi:10.1016/j.enbuild.2013.06.030

[Co-author, Conference Paper] Ramallo-González, A. P., Blight, T. S., Coley, D. A. (2012). Robust low energy design that accounts for occupant behaviour. 1st International Conference in Building Sustainability Assessment, Porto, Portugal

Presentations

[Conference Presentation] “The Impact of Occupant Behaviour on the Energy Consumption of Low Energy Dwellings” (August 2012). COBEE, Boulder USA

[Symposium Presentation] “Modelling Occupant Behaviour in Passivhaus Buildings: Bridging the Energy Gap” (September 2011). DeMontfort University, Leicester, UK

[Conference Presentation] “Buildings Don’t Use Energy, People Do” (June 2011). University of Bath, UK

[Poster Presentation] "Occupant Behaviour in Passivhaus Buildings: Bridging the Energy Gap" (January 2010). Climate Change & Sustainable Futures Mini-Conference. University of Exeter, UK

Contents

List of Figures

List of Tables

Introduction

Problem Statement

There is a large demand to reduce the energy demand of the built environment, and hence its contribution to anthropogenic climate change. In 2013 homes were responsible for 17% of all carbon dioxide emissions in the UK and hence play a key role in mitigation strategy (Department of Energy & Climate Change, 2014). The UK government is responding to this using incremental increases in building standard, and has stipulated that all new dwellings after 2016 will be 'zero-carbon'. These improvements are measured at the design stage however, which is a key point – measurement of performance post–occupancy is not standard practice, and where published the performance of buildings tends to deviate - often dramatically upward - from the design objective (Bordass, 2001; Gill et al., 2011).

Understanding the operational energy of a dwelling is highly complex and dependent on a number of physical, technical and social variables (Guerra Santin et al., 2009; Wei, Jones, & de Wilde, 2014). While many of these determinants are implicit to the design (e.g. building massing, orientation, form, materials, systems, etc.) the end-user is typically overlooked, despite their attitudes and actions being significant drivers of building energy use (Socolow, 1978). The effect of this probable oversight is not well-understood or accounted for, and requires further study.

Overview of Thesis

This thesis is comprised of five parts. Part 1 is a literature review, containing six sections. The first two sections of Part 2 document the development of a methodology to generate stochastic behaviour profiles representative of UK households, while the third section describes the development of a behaviour survey. Part 3 of this thesis describes a novel method for use of high-resolution stochastic behaviour profiles for thermal simulation of buildings. Part 4 documents the measurement of attitude and behaviours of a number of social housing tenants living in Passivhaus flats in Exeter, UK. The final part of this thesis, Part 5, discusses the results of the preceding work in the context of design in a commercial environment, and reflects on the methodological approach to both major aspects of the work.

For clarity and reference, introductory abstracts precede Parts 1, 2, 3 and 4 and summaries follow.

The Appendix contains one example of a contribution to knowledge from this body of work (in the form of a peer-reviewed journal article) and copies of both Phase 1 and Phase 2 of the occupant surveys discussed in Parts 2 and 4.

Statement of Thesis

The main body of this work provides evidence in support of the following hypothesis:

The influence of varied occupant behaviours on the energy performance of a set of otherwise similar dwellings is significant and, while difficult to measure, can be accounted for in dynamic thermal simulation.

Part 3 of this dissertation supports this claim by demonstrating how the simulation of occupant activity in a home can be representative of a sample of measurements from dwellings. Part 5 of this thesis discusses the limitations of this methodology. It is recognised that Part 4 of this thesis describes qualitative measurements which, due to a small sample size, are limited in wider application.

Part 1 Literature Review

The first part of this thesis describes the context of this research and builds a case for the work undertaken based on primarily academic literature. There is growing concern over the contributions from the built environment to anthropogenic climate change, in the form of CO_2 and other greenhouse gases associated with maintaining comfortable indoor environments in buildings. This leads to public pressure, and legislation is responding to this pressure in the UK, where the construction industry is facing stricter standards of building environmental regulation – standards which are incrementally increasing, forcing improvement in building performance. One milestone target is for housing designed after 2016 to be zero-carbon by design. These improvements are measured at the design stage however, which is a critical: monitoring and measurement of the actual performance of new buildings is not mandatory, and therefore discrepancies between design and in-use energy causes the efficacy of the legislation to be diminished or destroyed.

Understanding the in-use or 'operational' energy (the former term normally reserved for non-domestic projects) is highly complex and dependent on a number of physical, technical and social variables (Guerra Santin et al., 2009; Wei et al., 2014). While many of these determinants are implicit and decided at the design stage –building massing, orientation, form, materials, passive systems (e.g. natural ventilation strategy through opening windows) and active systems (e.g. heating strategy using gas boiler driven hot water circuit and radiator); normally overlooked at the design stage are the attributes, attitudes and actions of building users, which are shown to be significant determinants of building energy use.

Occupant behaviour is postulated to share a larger percentage of the overall building energy-use where the use of systems is minimised, as it is in very low-energy designs such as Passivhaus Certified buildings, where the average heating energy use of a building in a European climate is 15 $kWh.m^{-2}yr^{-1}$. In such spaces gains from occupants are relied upon for a 'baseload' of space heating, and as such the occupants themselves can be considered a major part of the heating system.

Achieving low and zero-carbon building is a difficult undertaking due to this complexity. Based on this literature review, this thesis aims to contribute to research and understanding using the methodology defined in Part 1.

1.1 Climate Change and the Built Environment

Anthropogenic Climate Change

The Stern Report in 2007 highlighted the severity of the changes in global climate, with a strong likelihood of temperatures rising beyond 5°C in a business as usual scenario - approximately the same increase experienced since the last ice age (Stern, 2007). Stern approaches the subject from an economic perspective he proposes that the cost of inaction is more costly than the cost of action, based on the effects of radical climate change.

The effects of anthropogenic climate change have been significant, with one study (Rosenzweig et al., 2008) showing climate change responsible for 80 cases of negative impact from a changing local climate. Effects of global climate change include loss of major ice sheets, accelerated sea level rise and de-stabilised ecosystems (including our own food production). The Intergovernmental Panel on Climate Change (IPCC) undertook detailed modelling of various climate scenarios and show that an atmospheric level of CO_2[1] stabilised at 350ppm would result in no further cumulative greenhouse gas (GHG) emissions (Griggs, Maskell, & IPCC, 1997), however measurements of the current atmospheric level of CO_2 show that the figure has not dropped below 350pmm since 1988, and at the time of writing is currently 395ppm (NOAA-ESRL, 2014).

Kyoto Protocol

The international Kyoto protocol was ratified in 2007 and for the first time clear targets were agreed by a community of countries for reduction of GHG emissions through the immediate target of a collective 5% reduction in GHG emissions over 2008-2012 period. Of this, the UK committed a negotiated 'fair share': a 12.5% reduction in emissions.

A second commitment phase of the Kyoto Protocol 2012-2020 failed to be widely adopted, with many industrialised countries pulling out including Canada and New Zealand . Post-Kyoto negotiations have included annual United Nations Climate Change Conferences (2007 - 2013) and the 2014 UN Climate Summit, at which India, Russia, Canada and Australia did not attend. The news that large private foundations (such as The Rockefeller Fund) were withdrawing from investment in fossil fuel

[1] Here CO_2 is used to refer to CO_{2e}, which describes the impact of other greenhouse gases such as methane, nitrous oxide, and fluorinated gases.

industries to a total of $50 billion leads to the idea of a new wave of motivation from the private sector to reduce GHG emissions where governments appear to have stalled (Bloomberg News, 2014). This indicates that global leadership in environmental design of buildings could come not only from government legislative requirements or local planning offices but from aspirational private businesses who are seeking to invest in more long-term sustainable business models.

Climate Change and the United Kingdom

Here in the UK, the Climate Change Act (Great Britain, 2008) was the proceeding legislature to Kyoto which committed the United Kingdom Government to reduce CO_2 by 80% by 2050 compared to a 1990s baseline. This was an increase from the figure of 60% stated in the 2007 White Paper on Energy due to ongoing research and investigation into the effects of climate change (Griggs et al., 1997; Rosenzweig et al., 2008). This target is considered an ambitious one, requiring a concerted effort from every sector of the UK economy.

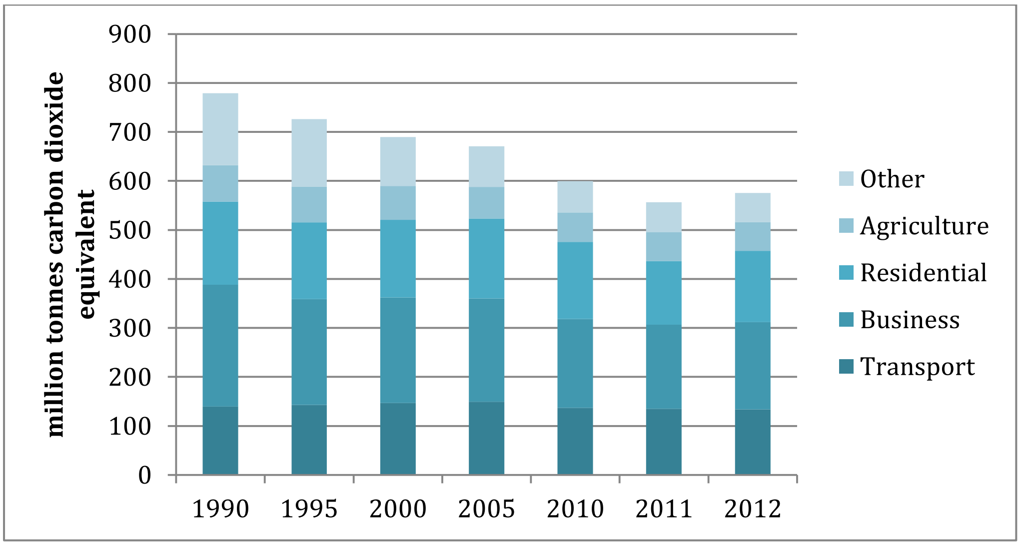

FIGURE 1.1 - NET CO_2 EMISSIONS BY END-USER IN UK.

Figure 1.1 shows a breakdown of net carbon dioxide emissions by end-user in the UK, indicating that residential emissions have consistently been a large part of the UK carbon dioxide use.

Climate Policy Post-Economic Crisis

Since 2008 - the beginning of the financial crisis – high rates of unemployment and insecure budgets has brought about a shift in the framing of climate change policy, from an environmental issue to an economic one. When political leaders met at the Copenhagen Climate Summit in 2009, there was great pressure to respond to these economic concerns from across Europe, and the talks ended without any major resolutions (Dubash, 2009). In the following two years, former European Commission President José Manuel Barroso struggled to maintain the potency of proposed climate directives (Rogers-Hayden, Hatton, & Lorenzoni, 2011). This shift in framing has been reflected in government organisation also: the UK's Department for Energy and Climate Change (DECC) was established in 2008 with the aim to connect energy and environmental issues, and current European Commission President Jean-Claude Juncker has shifted climate and energy in the remit of a single Commissioner (Schoenefeld, 2014).

Regulatory Response to Climate Change in the Building Sector

In December 2006 the UK Government announced a rapid transitioning of new buildings to 'zero carbon'; this was in light of the Climate Change Act. With the built environment counting for around 36% of the UK's total GHG emissions (Z. Tian & Love, 2009), building energy performance policy will play a key role in the decarbonisation efforts. This mirrors the wider situation across Europe, where buildings account for 40% of the total energy consumption (European Commission, 2010).

The BRE introduced the Standard Assessment Procedure (SAP) in 1995, and it uses a similar principal to that described above to assign an energy rating to a dwelling from 0-100+, where >100 is a net exporter of energy. The SAP methodology is the required energy assessment methodology demanded by Building Regulations Part L1, and has received regular updates, the most recent version being SAP 2012. While the SAP rating of a dwelling is demonstrated to be linked to energy use, the SAP has also faced criticism for its poor predictive power (Moutzouri, 2011).

Considering these targets, the continued expansion of the building sector is a significant concern; new buildings that are not built to a high energy standard are only going to further increase the consumption of the national building stock. The Code for Sustainable Homes (CSH) (DCLG, 2006) announces plans for up to 240,000 new homes per year to help current housing shortages and overcrowding. Low demolition and refurbishment rates of the existing housing stock mean that the majority of these new dwellings will only be adding to the mounting energy demand from the residential sector.

The enormous technical and logistical challenge to reduce total stock emissions by 80-90% by 2050 is evident. Any new buildings will need to go beyond operational zero-carbon in order to make positive contributions to reducing net GHG emissions over the baseline. In addition over two-thirds of 2050's anticipated housing stock already exists, therefore a large amount of planning and improvement measures need to be taken to reach our various goals (A. Power, 2008; Ravetz, 2008).

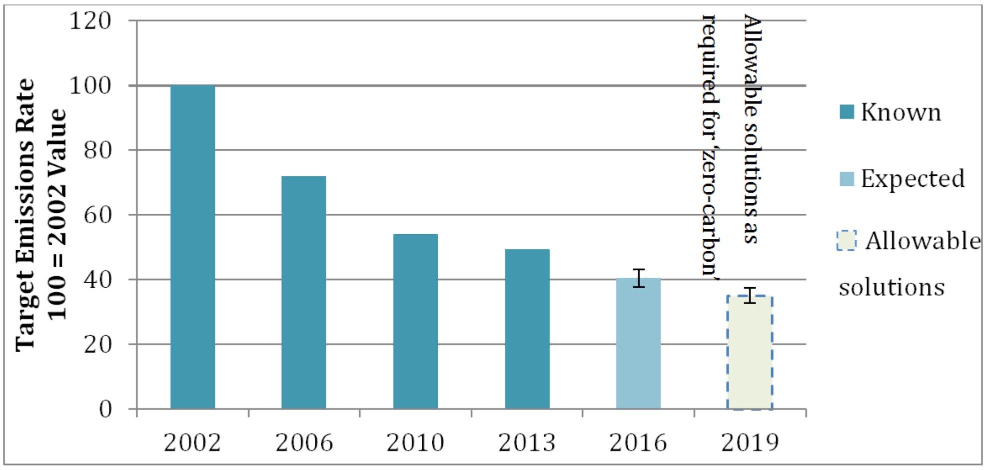

FIGURE 1.2 – UK BUILDING REGULATIONS - UPDATES TO APPROVED DOCUMENT PART L; PAST, PRESENT AND ANTICIPATED IMPROVEMENTS TO THE TARGET EMISSION RATE (TER). DATA: (DCLG, 2007A)

Figure 1.2 shows the development of UK Building Regulations Approved Document Part L 2B from a 2002 baseline and projected to 2016 where a further 10% reduction is expected, and 2019 where a complete reduction is anticipated through Allowable Solutions, thus reaching near 100% reduction in regulated CO2 emissions under this performance criteria, and nearing 'Zero Carbon' (generally considered as **net** zero CO_2 emissions on site). Note UK Part L 2B refers to non-domestic buildings. Domestic buildings face similar regulatory pressure, though the government has commited to 'zero-carbon' homes by 2016, meaning zero carbon will be required for all planning submissions submitted after 2016 legislation comes into effect (likely to be April 2017).

1.2 Zero Carbon Buildings in the United Kingdom

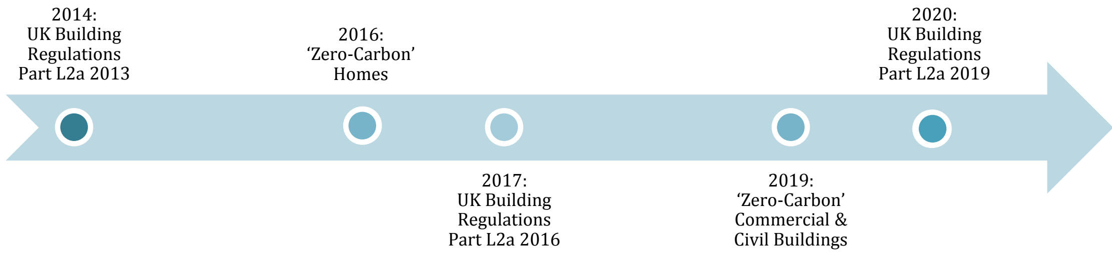

FIGURE 1.3 – TIMELINE TO 'ZERO CARBON' IN THE CONTEXT OF UK BUILDING REGULATION AND COMMITMENTS

While the terms 'zero-carbon' or 'carbon-neutral' are widely used to describe the idea of no net contribution of carbon dioxide emissions, there is a wide-range of specific meanings and methods under the heading. It is important to specify what is meant when referring to zero-carbon housing.

Originally, within the UK context, the definition of 'zero-carbon' homes was established in December 2006, when the Code for Sustainable Homes was introduced as a tiered sustainability rating system, from current building regulations to the envisioned 'zero-carbon' home achieving Level 6. The definition was stated: "Net carbon emissions from *all* energy used in the dwelling are zero or better", thereby incorporating building code regulated energy (heating, hot water, lights, and ventilation) and unregulated operational energy (cooking and appliances).

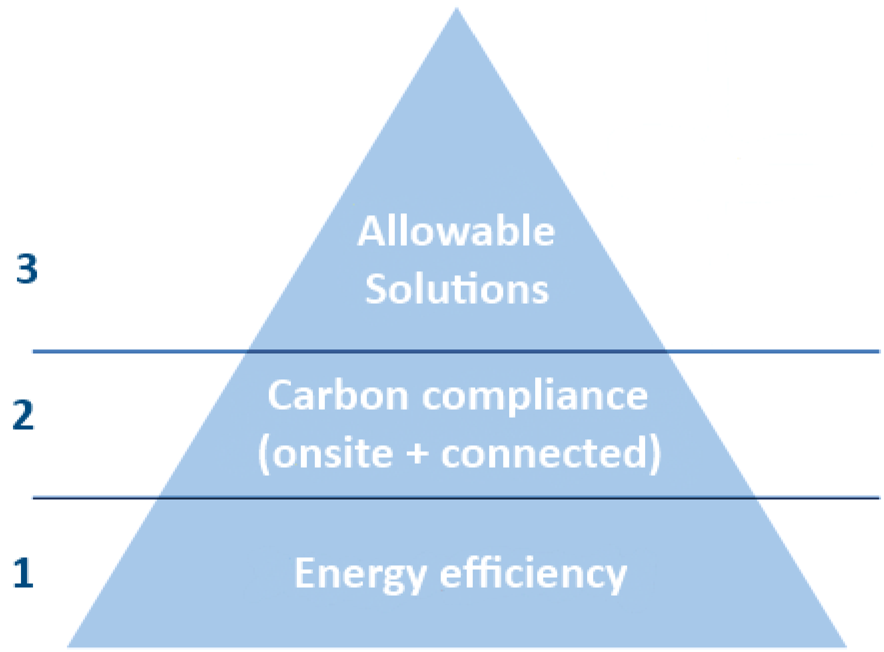

Figure 1.4 – The proposed hierarchy for the delivery of zero-carbon housing in 2008 (DCLG, 2008)

In the 2008 consultations the Government's preferred hierarchy for the delivery of zero-carbon homes in the UK are revealed, as seen in Figure 1.4. This triangle of carbon offset measures firstly prioritises energy efficiency measures, stating that: "high energy efficiency standards will help secure energy and carbon savings over the lifetime of the building, without relying on the investment or behavioural choices that occupants will make." The second level of the carbon abatement hierarchy is in carbon compliance for onsite and directly connected heat. This covers Low and Zero-Carbon (LZC) technologies that are onsite, and connected heat/water networks. It also covers directly connected off-site electric, which is not part of the pre-existing licenced distribution network. In the same document, the results of modelling technology combinations for the various levels of carbon compliance (for each level of the code) show that with a higher compliance level comes fewer options for technology combinations, and admitted that none of the options presented eliminated 100% of regulated emissions plus those from appliances and cooking – the 'net operational zero carbon home'.

The third and final tier of the Zero-Carbon hierarchy has received a lot of attention, described by McLeod as "…effectively introducing a buyout clause" (McLeod, Hopfe, & Rezgui, 2012a). 'Allowable solutions' are announced to be measures by which the residual CO_2 emissions can be offset with either export of heat and electricity or via direct investment into local renewable energy/retrofitting projects. This announcement was welcomed by the Zero Carbon Hub (ZCH) who noted that this would go some way to alleviate the bias against small sites with less space for renewable technology (The Zero Carbon Hub, 2009).

Regardless of the somewhat divisive Allowable Solutions, the Energy Efficiency and the Carbon Compliance Levels are of great impact on the resultant level of CO_2 reduction. The Fabric Energy Efficiency Standard (FEES) was proposed in 2009 by ZCH (The Zero Carbon Hub, 2009), using the metric of space heating and cooling demand per internal unit floor area per annum ($\mathrm{kWh.\,m^{-2}a^{-1}}$). An alternative metric of $\mathrm{kgCO_2m^{-2}a^{-1}}$ was proposed at this time, but the outcome of discussions found the metric already popularised by the Passivhaus certification based on energy demand rather than carbon was easier to comprehend to house-builders, and already had international recognition.

As for kilowatt-hours, the ZCH clearly state in the definition that this is heat *demand*, rather than heat *consumption*; the efficiency of the energy delivery method is not taken into account. Floor area is not so well defined in the document, and it remains to be seen whether this is a Passivhaus-style treated floor area or another interpretation. Equally important to normalising for floor area is to normalise for occupancy, giving a fairer representation of space usage, and encouraging more efficient use of space.

The ZCH propose two levels of efficiency for heating energy use in spaces to account for the constraints in the form of different housing types: $39\ \mathrm{kWh.\,m^{-2}a^{-1}}$ for multi-residential and mid-terraced properties, properties which share more than one adjacency to other heated buildings; and $46\ \mathrm{kWh.\,m^{-2}a^{-1}}$ for end-terrace, semi-detached, and detached properties, which have greater heat loss due to exposed elevations. Figure 1.5 illustrates this. The rationale for this simple heuristic is that a similar fabric specification can meet targets across a range of building types. However, this is rather crude as the building performance actually depends on a variety of factors, including orientation, microclimate, and building form.

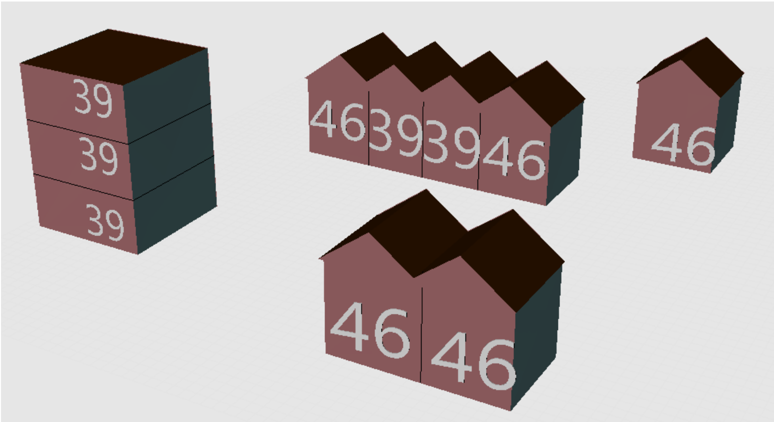

FIGURE 1.5 – PROPOSED FABRIC ENERGY EFFICIENCY STANDARDS (UNITS IN KWH.M^{-2}A^{-1}) FOR DETACHED, SEMI-DETACHED, TERRACED, AND APARTMENT DWELLINGS, FROM (THE ZERO CARBON HUB, 2009).

The 'revised approach' to zero carbon housing in the UK

In 2009 the Government sets out the revised definition of zero carbon in its 'Have Your Say' report (The Zero Carbon Hub, 2010) and confirms it in the 2011 Budget (H.M. Treasury, 2011). The scale of the Carbon Compliance level is radically altered, from "all energy" to "all regulated energy". This definition excludes all cooking and appliance energy – among the most volatile energy loads of the household and stated by the Department of Communities and Local Government to be 21% of the average domestic carbon emissions by source (DCLG, 2007b). In addition to this it is confirmed that the emissions released during the manufacture and construction of the dwelling - which can account for up to 50% of the 80-year emissions from a low-energy dwelling (McLeod, 2007) - will not be considered. It is fair to state that the definition of zero carbon housing has been revised to leave a misleading reflection of the atmospheric CO_2 accounted for.

Zero-carbon buildings internationally

In 1997 the United Nations Framework Convention on Climate Change adopted the Kyoto Protocol. A total of 37 countries committed themselves to a reduction or stabilisation of GHG emissions, though a number did not ratify the commitments, most notably the USA. In accordance with these commitments, many of the countries have adopted stricter building energy certification, and/or plan to increase performance standards of building stock. Due to differences in climate, among other factors, there is no 'one size fits all' solution.

Zero-carbon buildings Europe

The European Commission's 2002 Directive 2002/91/EC on the energy performance of buildings called for EU Member States to develop building energy performance schemes with particular regard to heating, cooling, design of the building, and renewable technology. Paragraph 10 reads:

> "The energy performance of buildings should be calculated on the basis of a methodology, which may be differentiated at regional level that includes, in addition to thermal insulation other factors that play an increasingly important role such as heating and air-conditioning installations, application of renewable energy sources and design of the building."

In 2008 the European Commission again addressed the need for energy efficiency measures in a document entitled 'An action plan for energy efficiency' (European Commission, 2008):

> "Calls on the Commission to propose a mandatory requirement that all new buildings needing to be heated and/or cooled shall be constructed to passive house or equivalent non-residential standards from 2011 onwards: including a requirement to use passive heating and cooling solutions from 2008."

Here the document specifically refers to the German Passivhaus standard, which is addressed in more detail in Section 1.3.

The Directive is unspecific when it refers to 'passive heating and cooling solutions' but in general terms this embraces all design techniques that take advantage of the local climatic conditions to control the environment within a building, for example intelligent placement of brise-soleil can block the summer solar gains while allowing winter sun to pass, through using the correct angle. Other examples of passive heating and cooling solutions include, but are not limited to: natural ventilation, thermo-siphoning and thermal mass.

In Europe, the EPBD recognises over 30 different low-energy building standards, in part due to the 2002 Directive. To tackle this variety of similar accreditation, González and Díaz (González, Díaz, Caamaño, & Wilby, 2011) propose a solution which enables one performance index to cover every conceivable building in every climate.

The potential for such a universal indicator is great, though is limited to its reliance on an up-to-date database of the performance of similar notional buildings to compare the measured performance to, something which would require excellent management of very large datasets, and some negotiation regarding level of complexity (parameters included in a non-linear function describing energy use/carbon emissions per unit area of space). They define two energy efficiency indices, EEI_B, EEI_B^*, depending on what aspect of energy performance is being measured consumption or emissions respectively, shown in (1.1) & (1.2). The performance indicator of the reference building C_{RB} ($kWh\, m^{-2}$) or E_{RB} ($kgCO_2\, m^{-2}$) is normalised for floor area, and the indicators are applied to particular building classifications as described by the EPBD and US Energy Information Administration, e.g. hospital, school, offices.

$$\boldsymbol{EEI_B = \frac{C_{AB}}{C_{RB}}} \quad \textbf{(1.1)}$$

$$\boldsymbol{EEI_B^* = \frac{E_{AB}}{E_{RB}}} \quad \textbf{(1.2)}$$

The BRE use a very similar method to assess compliance with UK Part L regulation (i.e. Building Regulations Part L England & Wales). One drawback of such a method is that it is necessary to pick from a number of fixed spacetypes with predefined usage profiles for lighting, occupancy, equipment and DHW use. In some cases these profiles are unrealistic, for example the NCM profile for school occupancy which is relatively reflective of a UK school during term time, but over holidays is set to be constantly occupied. This can lead to biases in the compliance routes (in the example above, a school with efficient cooling systems would perform well, though In reality the cooling may not be required nearly as often as the NCM profiles suggest), which make it easier to perform well using systems which may in reality not be the right ones for the job.

Another issue with this standard is that the absolute energy of the Actual Building is not taken into account, only its performance against the Reference Building, therefore a building may find an easier compliance route by choosing a less efficient system overall.

It is best to think of such compliance tests in the same way one might consider a pollution test on a motor car – the engine is ran through some specific load profile, and examine the air quality produced. A necessary standardisation to provide an easy compliance test and result, but it ignores the fact that one vehicle's engine may not be designed to run under the same conditions as another, for example in the case of an off-road vehicle and a compact car.

1.3 Low-Energy Performance Certification

There are a great number of schemes to assess the performance of buildings. Here 'performance' can apply to a wide variety of measurable parameters, from designed or measured energy parameters such as heating or cooling energy, to parameters indicating local ecological sustainability, to measurements of wellbeing and happiness of building users. This thesis focuses on the energy-specific range of parameters, and a few key schemes are introduced below.

Code for Sustainable Homes

The Code for Sustainable Homes (CfSH) is an environmental assessment method, now a Government-owned scheme brought in under the EPBD. The energy efficiency component of the methodology is dependent on the UK Part L regulatory method - In the CfSH projects are awarded higher levels of the code for gaining more credits, from Level 1 (10% better performance than 2006 UK Part L regulation) to Level 5 (zero regulated emissions) and Level 6 (zero regulated and unregulated emissions). As Part L1A of building regulations has set higher efficiency targets, the energy performance requirement of any new building is equivalent to Code Level 3.

CfSH is set to be abolished and replaced in 2015 by a new BRE standard, the Home Quality Mark. It is anticipated that the new standard will cover much the same areas as CfSH, adding embodied energy/carbon considerations and possibly more credits available for energy performance between Levels 4 and 6.

LEED

In terms of growth rate and international take-up, one of the most successful holistic energy certification schemes is the Leadership in Energy and Environmental Design (LEED) certification developed by the US Green Building Council. LEED now encompasses 79 regional chapters as well as having certified buildings in 135 countries, including the offshoot organisations LEED Canada and LEED India. LEED is a holistic certification, meaning it considers the whole construction process from planning through construction to on-going use. Credits are awarded for good planning and design in each category, with some categories worth more credits than others; for example, most relevant to our topic is 'New Construction v2009 *Optimize Energy Performance* EAc1', worth up to 19 credits depending on the building fabric performance compared to a notional equivalent building meeting the ASHRAE Standard 90.1 2007. The LEED methodology has been used in many countries around the world, and is one of the most favoured environmental assessment methods (Cole, 2005).

A criticism of the LEED standard, and similar credit-based environmental assessment schemes such as Code for Sustainable Homes, is that the credits cover a wide range of environmental themes, and are often transferred to multiple climates across the globe. Points systems therefore can be 'gamed' to understand the easier credits to reach in certain contexts, to achieve the greatest credit yield at the lowest cost (Cole, 2005).

MINERGIE Quality Labels

The Swiss standard MINERGIE was originally developed in 1994, with the first two houses achieving the label the same year. Since then the standard has developed to a number of different areas from passive building design (MINERGIE-P) to ecological materials use (MINERGIE-ECO). The standard has strong support from the private sector in Switzerland, and 38,000 completed projects internationally. An interesting aspect to the standard is that it accepts building clusters, which are 'spatially and visually' connected (Hall, Geissler, & Burger, 2014), making for efficient organisation and roll-out on large scales. In 2011 the MINERGIE-A standard was introduced, which prescribes a net-zero primary energy balance for heating, hot water, ventilation and auxiliary energy (but not lighting or appliance use). Nearly every MINERGIE-A standard building is connected to onsite PV to help meet this balance. There has been no wide-scale monitoring of MINERGIE-A buildings in-use, though as it is a relatively new standard it is hoped this will be forthcoming.

Passivhaus Standard

The Passivhaus Institute gives the following definition of their energy efficiency and thermal comfort standard:

> "A Passivhaus is a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air."

The Institute goes on to define a space conditioning target based upon this precursor. Given a minimum fresh air flow rate for one person is 30 m^3h^{-1} (according to the DIN 1946 – health criterion), and at 21°C and standard pressure (when air has a heat capacity of 0.33 $Wh.m^3K^{-1}$), fresh air can be heated by a maximum of 30 K (to 51°C) in order to avoid dust carbonisation or the burning of small dust particles in the air. This results in the following capacity needed per person:

$$P_{pers} = 30\ \mathrm{m^3h^{-1}pers^{-1}} * 0.33\ \mathrm{Wh.m^{-3}K^{-1}} * 30\ \mathrm{K}$$
$$= 300\ \mathrm{W.pers^{-1}} \quad \textbf{(1.3)}$$

therefore the heating of the supply air can provide 300 $\mathrm{W.pers^{-1}}$. Assuming 30 m^2 of living area per person, this would result in 10 Wm^{-2} of living area, regardless of the climate. This is a peak load, i.e. the values are based on the day with the highest heat demand. This is known as the *climate independent space-heating requirement*. In order to meet this criterion, a Passivhaus will require different levels of insulation depending on the climate zone: more in Stockholm, less in Rome. In Central European testing, buildings that meet this requirement tend to achieve an average annual space heating use of 15 $kWh.m^{-2}a^{-1}$, and though this figure is widely considered a requirement of the standard, it is in fact a target – the peak load of 10W/m2 is the overarching requirement of the standard.

Elements of the Passivhaus approach are as follows:

- Form-factor – Where possible, the design of the building is such that the surface area (external) to treated-floor-area ratio is low
- Superinsulation – Passivhaus buildings have a well-defined thermal envelope, with detailing to prevent thermal bridging and air leakage.
- Triple-glazing – along with a well-insulated envelope, triple-glazing helps to maintain a high and comparitivly uniform internal surface temperature, to combat the draughts caused by convection near cold glazed surfaces.
- Heat recovery and supply air heating – Air is supplied to spaces continuously, with the flow regulated to ensure minimum fresh air requirements are met. Heat exchange units are used to transfer the heat from the exhaust air to the incoming fresh air. The supply airstream is typically also heated when required.
- Solar gain – Modern glazing units allow for south-facing windows to be net-positive heat gains, however north windows facing in other directions are usually limited in area.
- Efficient appliances – Appliances with high efficiency ratings are typically required to keep to the 120 $kWh.m^{-2}a^{-1}$ limit on primary energy use.

Dishwashers and washing machines are usually connected to a hot water supply, and airing facilities are preferred over hot air driers.

- Use of renewable technologies – There is no requirement to use renewable technologies

The Passivhaus principle is examined thoroughly in the 2001 report ‘Cost Efficient Passive House as European Standard’ (CEPHEUS) (Schnieders, 2003), in which 221 housing units in five EU countries are built to Passivhaus standards, and a measurement campaign of at least one heating system conducted in 11 of the 14 projects involved. The evaluation concluded that the work was a ‘complete success’ in terms of the concept viability, measured space heating targets, applicability to a range of building styles and constructions, project-level economics, and occupant satisfaction.

One of the most interesting results of the CEPHEUS project was the accuracy in estimation of heating use – Schnieders demonstrates that the Passivhaus Planning package (PHPP) is remarkably close to predicting measured energy use, when normalised for weather (Schnieders & Hermelink, 2006).

Passivhaus dwellings have since been built in countries around the world, for a variety of occupancies, from schools to multi-family dwellings to offices. Certification has been awarded to over 30,000 buildings, on a voluntary basis in Europe since its inception in the early 1990s (iPHA, 2012).

While there are a number of positive aspects about Passivhaus buildings, they are not the ‘panacea’ for housing. A number of issues are associated with the stringent certification:

- Loss of Net Floor Area (NFA) – The high levels of insulation required mean that the walls of a Passivhaus reduce the available NFA compared to a comparable notional building.
- Low Humidity levels – in the heating season, because cold air is brought in at a minimum ventilation rate and warmed to a higher temperature, the Relative Humidity (RH) can drop considerably in the space, causing some occupants discomfort (Siddall, 2012a).
- Expense – it has been shown in a number of case studies that the initial outlay of a Passivhaus compared to that of a building built to standard regulations is on the order of 8-16% (De Selincourt, 2013; Newman,

2012), though it has also been shown by PHI and Newman to have a payback period up to 25 years.

- Overheating risk – due to the airtight envelope and high insulation, there is less cooling through leaks in the constructions, and overheating must be controlled by occupant behavioural adjustment (McLeod, Hopfe, & Kwan, 2013; Sameni, Gaterell, Montazami, & Ahmed, 2015)

FIGURE 1.6 – EUROPEAN PROJECTS STUDIED OVER THE CEPHEUS PROJECT (SCHNIEDERS, 2003)

1.4 The role of the Passivhaus standard in UK climate change and energy targets

While the Energy White Paper (Department of Trade and Industry, 2007) estimates carbon savings in the residential sector to be somewhere in the region of 4.7-7.6 $MtCO_2$ by 2020 relative to a 2006 baseline of 40 $MtCO_2$, this is only a 12-18% reduction, falling short of the required 40% to keep on track with GHG emission reduction target of 80% by 2050. The Energy White Paper also stipulates that Zero Carbon homes will contribute to a 1.1-1.2 $MtCO_2$ reduction in UK CO_2 over 2006 levels by 2020, however it is worth noting that these savings are based on the original definition of Zero Carbon, not the 2011 revisions. Given this, it is evident that the current course of policy does not meet the required reductions.

In addition to pressures from the perspective of reducing carbon emissions, the efficiency of the stock also requires improvement to tackle fuel poverty and energy security issues.

It was the US Energy Crisis in the 1970s that ignited the foundation of the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) and the first performance requirements in the US were implemented three months later (Kirkwood, 2010).

In contrast, fuel poverty is not a widely researched issue in the US. An article in a US journal from 2006 highlights the progress on the subject of fuel poverty in the UK including the Warm Homes and Energy Conservation Bill which was passed in 1999, and argues the US - of which 15% of the population is in affected by fuel poverty as defined by UK indicators - can learn a lot from UK approach to fuel poverty (M. Power, 2006; UK Government, 1999). In more recent times, the EU Fuel Poverty Network has been established with support from the Eaga Charitable Trust to study and further the dialogue on fuel poverty throughout the EU.

TABLE 1.1 – TAKE-UP OF VARIOUS INSULATION MEASURES UNDER LEVEL 1 (LOWEST TAKE-UP) AND LEVEL 4 (HIGHEST TAKE-UP) OF THE GOVERNMENT'S ENVISIONED 2050 PATHWAYS.

Measure	Number of households receiving measures (000's)	Fraction of potential addressed on completion of roll-out
Level 1		
Solid wall insulation (internal or external)	400.2	5%
Cavity wall insulation	2,288	25%
Floor insulation	3,570	30%
Triple glazing equivalent	2,366	10%
Loft insulation	1,117	5%
Improved air-tightness	62.8	0%
Level 4		
Solid wall insulation (internal or external)	7,659	96%
Cavity wall insulation	8,756	96%
Floor insulation	11,388	96%
Triple glazing equivalent	22,641	96%
Loft insulation	21,440	96%
Improved air-tightness	24,050	96%

Models of four levels of energy efficiency and consumer change between now and 2050 are presented by the Department of Energy & Climate Change (DECC) in their 2050 Pathways Analysis. Insulation and stock efficiency options Level 1 and Level 4 are shown in Table 1.1, and are combined with some notes on changes in behaviour, for example the Level 1 scenario includes uptake of household air conditioning units and increasing levels of thermal comfort, whereas Level 4 scenario assumes no air conditioning in homes and 50% less hot water use. The resulting residential heating demand forecast (shown in Figure 1.7) indicate that only a high efficiency standard (i.e. Passivhaus or equivalent) of new homes can achieve a long-term reduction in total domestic heating demand (DECC, 2010). Given that this reduction (Level 4) can only be achieved by switching to "Passivhaus-style" buildings and a concerted effort to refurbish old stock, accompanied by reducing the average temperature throughout all rooms in the house to 16 $°C$[2](i.e. occupied rooms warmer than unoccupied rooms), there appears to be no room for new buildings which fall short of the highest standard of energy efficiency.

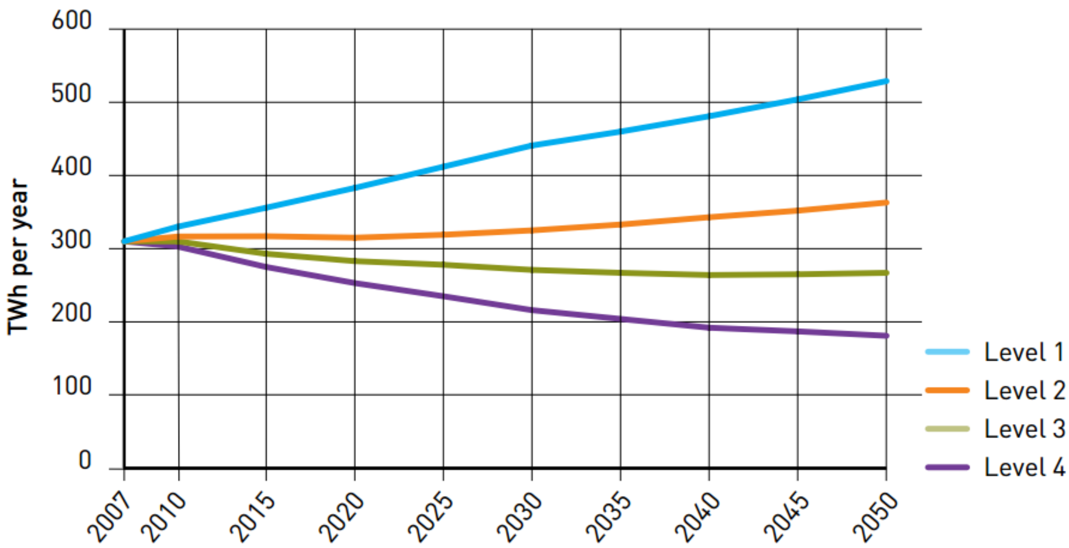

FIGURE 1.7 – TRAJECTORIES FOR TOTAL DOMESTIC HEAT DEMAND UNDER FOUR LEVELS OF CHANGE. FIGURE CREDIT: (DECC, 2010).

When one also considers the projected increase in cooling energy required by 2050, the case for Passivhaus building becomes even stronger. Figure 1.8 shows the 50 TWh of additional energy for cooling predicted for 2050, energy that has not at this

[2] From (DECC, 2010) – "Average internal temperature in UK households falls to 16 $°C$ by 2050, representing a significant decrease of 1.5 $°C$ on the 2007 winter average. The effect that internal temperature has on comfort and health varies depending on the type of occupant, activity levels and clothing. Children, the elderly and those with reduced mobility or certain health problems are more vulnerable to the cold than the general population. The evidence shows that 16 $°C$ is a safe minimum in occupied rooms for vulnerable groups. Department for Communities and Local Government (2008) Review of Health and Safety Risk Drivers, page 30."

stage been factored into the ZCH proposals on energy efficiency. When total annual loads are considered, DECC models show only the Level 4 scenario to deliver a net decrease in heating, cooling, and hot water energy demand.

While CSH and Passivhaus are not directly comparable, the former being a holistic certification with criteria ranging from water use to on-site bicycle storage; the latter focusing only on producing a very high energy-efficiency without any consideration as to how it is reached, or the larger picture. CSH has lately incorporated more credits to the energy-efficiency side of the standard, meaning that a Passivhaus Certification will achieve Level 4 CSH whilst minimising the reliance on renewable technologies, and creates a strong basis for a code Level 5/6 project.

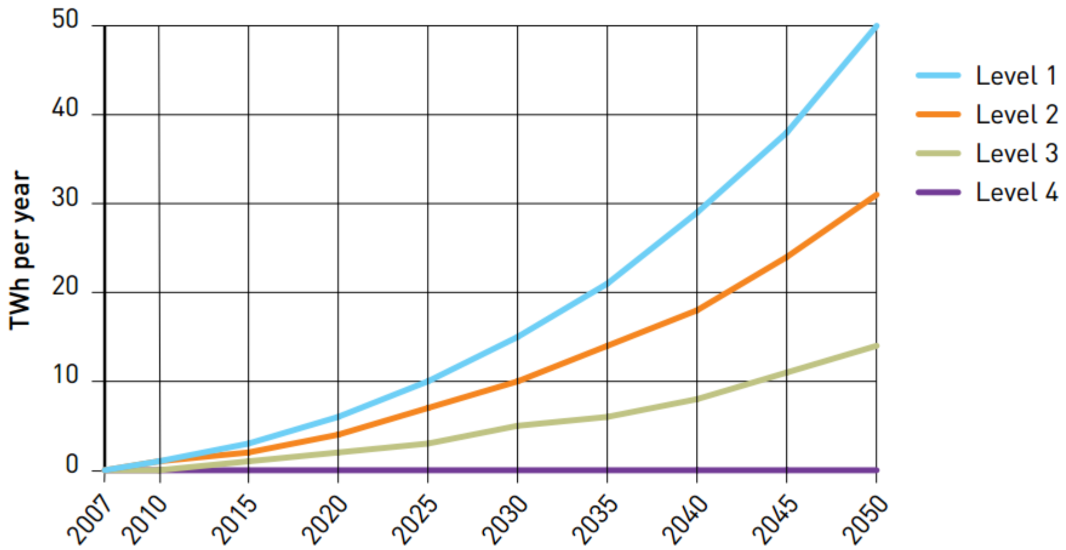

FIGURE 1.8 – TRAJECTORIES FOR TOTAL DOMESTIC COOLING DEMAND UNDER FOUR LEVELS OF CHANGE. FIGURE CREDIT: (DECC, 2010).

Adoption of the Passivhaus standard in the UK

In 2009 the Energy Savings Trust launched discussions, chiefly to decide on a metric for measuring heating use (Standardised Heat Demand, SDH) which aligned with the Passivhaus standard ($kWh.m^{-2}a^{-1}$) – an internationally recognised unit, as discussed previously - however discussions also touched upon the level at which the SHD should be set. The Energy Savings Trust report proposed that the limit to the SHD was set to a level between 15 - 25 $kWh.m^{-2}a^{-1}$; with adjustment occurring to take account of the building form (Hodgson & Energy Savings Trust, 2009).

Justification given by the ZCH task force for dismissing the Passivhaus standard and the Energy Savings Trust Advanced Practice Standard in favour of significantly weaker standards of energy efficiency are presented in the full report from the

Energy Efficiency Task Group (Zero Carbon Hub, 2009). Notably the comparative analysis of the energy performance standards presented in this report appears to overestimate the SHD of the Passivhaus, suggesting that it would result in a SHD between 23 and 29 $kWh.m^{-2}a^{-1}$, when modelled in SAP.

Currently the forum for the adoption of a PH standard is divided, with 47% expressing 'serious concerns' about whether a mass roll-out of PH specification buildings was buildable at all (Zero Carbon Hub, 2009), however the forum participants admit a lack of knowledge on low energy building and significantly underestimated the challenge presented by zero carbon. Key barriers to wide scale roll-out of PH appear to be the under-prediction of energy savings, and uncertainty about the buildability of the PH concept.

Another major concern over the adoption of a PH standard is the issue of the indoor air quality that comes with a sealed dwelling using mechanical ventilation systems for fresh air. In the ZCH report it states that the lack of experience and understanding of mechanical ventilation systems in the domestic sector mean that any progress on this front would be alongside intensive monitoring and technical research.

There is in fact a growing body of post-occupancy research studies correlating improved indoor air quality and occupant wellbeing in both, domestic and non-domestic low energy buildings ventilated by means of mechanical ventilation systems. Snijders *et al.* found that dedicated ventilation systems may slow down the development of Chronic Obstructive Pulmonary Disease (COPD) and prolong the independence of those affected by the condition (Snijders, Koren, Kort, & Bronswijk, 2001). Whilst Harving *et al.* (Harving, Korsgaard, & Dahl, 1994) demonstrated that the number of allergen producing dust mites and fungi in buildings was reduced by low indoor room humidity (RH) levels induced by a suitable ventilation system.

1.5 The 'Energy Performance Gap'

Design and construction of low- and net zero-carbon buildings is relatively common, particularly as mandatory legislation increases the required standards for the design and construction of buildings. There is increasing concern however, about a mismatch in the performance of a building compared to its designed performance (De Wilde, 2014; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; The Carbon Trust, 2011; Turner & Frankel, 2008). Energy performance is only one aspect of this gap, it is very likely that similar gaps exist in air quality, thermal comfort, water use, and acoustic performance, but in

As metering technology and data storage techniques are improving, the gap is becoming ever more apparent. The size of the issue is concerning, as there are reports of up to 2.5 times the energy use of the design being measured (Menezes et al., 2012). Understanding such a discrepancy is crucial to progress in the fields of high-efficiency building design, where it currently reduces the credibility of predictive simulation in the design sector.

This performance gap has been studied in the past two decades by many, including the notable CIBSE PROBE Project jointly funded by the UK Government and The Builder Group from 1995-2002 (Bordass & Associates, 1999; Bordass, 2001). This project has since led to other initiatives dedicated to closing the performance gap, including the development of the Soft Landings Framework, a voluntary process which seeks to ensure smooth transition through building design, construction and use (M Way, Bordass, Leaman, & Bunn, 2009; Mark Way & Bordass, 2005), and CIBSE RIBA CarbonBuzz – an online database where building operators can anonymously post both regulated and non-regulated energy use statistics for comparison to other similar buildings around the UK (Kimpian & Chisholm, 2011).

In simplified terms, this difference is attributed to a number of factors including:

- Simulation ≠ Design – within the project team there may be misunderstandings about the energy targets of the project, (Korjenic & Bednar, 2012; Menezes et al., 2012).
- Construction ≠ Design – Frequently it is discussed that onsite construction is not meeting design standards, whether it is meeting appropriate airtightness standards (Johnston, Wingfield, Miles-Shenton, & Bell, 2004),

insufficient care about thermal bridging or insulation levels (Menezes et al., 2012; Scofield, 2009), and it is likely that many inaccuracies in bringing a design to reality are falling short or standards and not noticed, due to the difficulty of finding problems under layers of constructions

- Simulation ≠ Use - Clients may not be able to provide detailed information on the anticipated uses of the building, and even if they provide perfect information about the expected usage of an unbuilt space, the simulation engineer still has a number of approximations to make, from local climatic conditions to representations of complex HVAC systems (Korjenic & Bednar, 2012)

- Use ≠ Design – It is very common for occupant behaviour to be pointed out as the reason for an energy performance gap – the building wasn't designed to be used as it is (Haldi & Robinson, 2008; Kimpian & Chisholm, 2011; Menezes et al., 2012). This should not be considered the 'fault' of the occupants or facilities management team however, the actual complexities of operations are rarely considered in detail during design. There are other wider influences to be accounted for such as social, cultural and technological shifts.

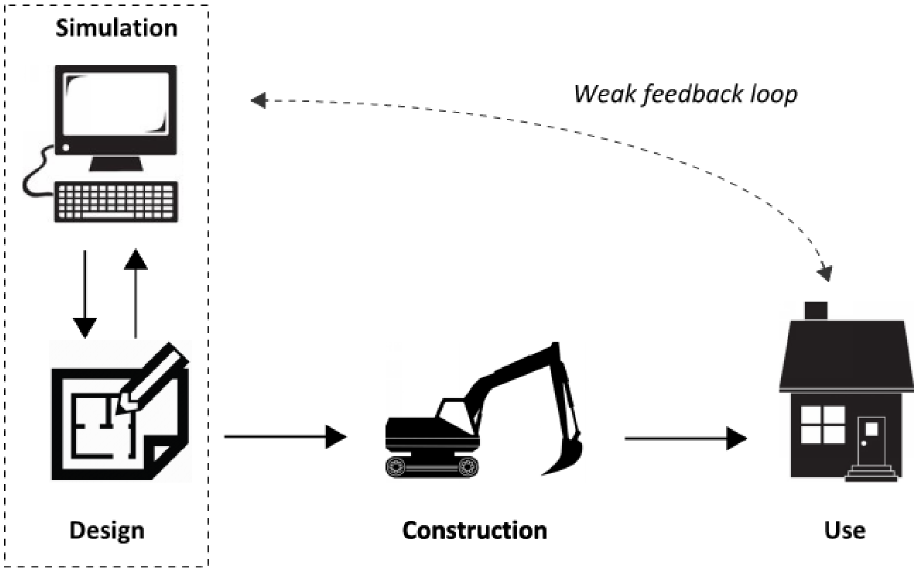

FIGURE 1.9 – ILLUSTRATION OF SIMULATION'S ROLE IN CONSTRUCTION FROM DESIGN TO OCCUPANCY.

FIGURE 1.9 illustrates the traditional role of simulation in the construction of a building. Typically simulation sits with design, and aside from high-level long term feedback, individual projects monitoring is not fed-back to the team responsible for design or simulation. The solid arrows indicate a typical flow of information, but each step may be imperfect, i.e. the four points discussed above.

1.6 The Role of Occupant Behaviour in Building Performance

Although on-going improvements to system efficiency, materials, and construction methods have significantly reduced the amount of energy used for space heating (Beerepoot & Beerepoot, 2007; Leth-Petersen & Togeby, 2001), studies have indicated that as buildings become more energy efficient, the behaviour of occupants play an increasingly important role in consumption (Guerra Santin, Itard, & Guerra-Santin, 2010; Haas, Auer, & Biermayr, 1998; Lee, Andersen, Sheng, & Cutler, 2009; Papakostas & Sotiropoulos, 1997). One can imagine this to be true in the extreme case of the Passivhaus, where a heating system is nearly replaced entirely by a baseload of incidental heat gains from occupant activity inside the home.

It is known that much of the discrepancy in energy consumption amongst buildings with similar constructions can be attributed to differences in occupancy patterns and occupant behaviour (Branco et al., 2004; Gill, Tierney, Pegg, & Allan, 2010; Lindén, Carlsson-Kanyama, & Eriksson, 2006). For example in research by Gill et al., in which a post-occupancy evaluation was carried out on a UK *EcoHomes* site, the contribution of energy behaviours accounted for 51% of the variance in heating energy use.

There is no definitive list of the ways occupant behaviour can impact energy usage. Though many have studied the measurable categorical variables for the purposes of statistical studies such as the Woononderzoek Nederland (WoON) Survey (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2013), with variables such as 'showers in minutes per week per household size' or 'hours per week mechanical ventilation in bathroom' these are not easily relatable to daily behaviour patterns. Occupants see their impacts on their immediate environment and in within the context of their daily activities. The palate of behavioural options available for altering energy consumption for the discerning occupant are wide-ranging and vary with technological/cultural shift, but some examples applicable to current housing include:

- Usage of thermostats – are they regularly reviewed?
- Radiator flowrate – are all radiators set to full flow, or have they been adjusted depending on the space?
- Bathing – efficient use of hot water in the shower/bath?
- Washing – efficient use of dishwashing/washing machine cycles
- Lighting – are more on than required?

- Lighting – consider timeswitches / IR sensors
- Curtains – drawn to keep heat in/out
- Draught control using internal doors

Karlsson et al. stresses the importance of building occupant behaviour when designing energy simulations, and also highlights the *difficulty* of doing so (Karlsson, Rohdin, & Persson, 2007). Wood and Newborough propose that behavioural change is a major untapped area for energy savings, however they argue that the diversity of understanding, attitude, and abilities are a salient barrier to change (Wood & Newborough, 2003).

In Part 1 of this work the contribution of occupancy differences in behaviour is closely analysed using a novel approach.

1.7 Measuring Occupant Behaviour

Efforts have previously been made to help develop consumer-centric programs to encourage energy-efficient behaviours, since the time of the 1970's oil crisis there has been concern about fuel security.

The Twin Rivers program was among the first of such interdisciplinary projects aiming to examine energy consumption changes through both technical (hard) and behavioural (soft) measures in a number of identical townhouses in Philadelphia, USA (Socolow, 1978). A salient conclusion of the study was that the energy consumption for space heating was substantially predicted by studying the user rather than the physical features of the property. After an energy-efficiency retrofit the rank ordering of consumption amongst the houses remains largely the same, in spite of major hard modifications.

Firth *et al.* recorded whole-house power consumption data for 72 dwellings over five sites in the UK over a two-year monitoring period (Firth, Lomas, Wright, & Wall, 2007). The mean annual energy use increased by 4.5% from one year to the next across the study, attributed to an increase in use of 'active' (defined as appliances which have no standby power usage and are turned on by the occupant, e.g. iron) and 'standby' appliances (appliances with three basic modes of operation, standby, in-use, or switched fully off), as illustrated in Figure 1.10. 'Cold appliances' refer to refrigeration which is similar to a standby consumption except the pattern of activation or cycling is not strongly related to occupants 'using' the item. It was also observed that the increase in usage was due to the low and high-energy users rather than the moderate energy consumers, with an increase of 11% from the low-energy group, and an increase of 5% from the high-end users.

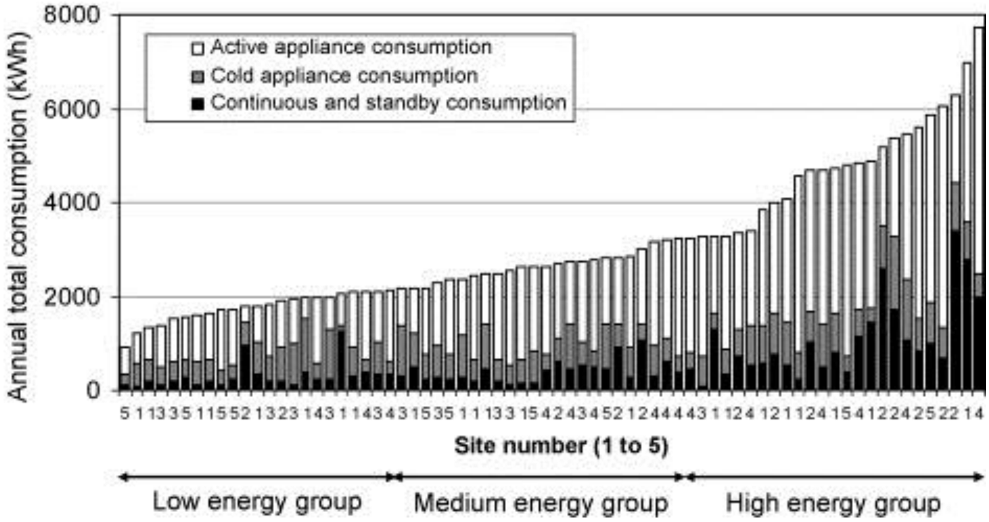

FIGURE 1.10 - ANNUAL CONSUMPTION SPLIT BY APPLIANCE CONSUMPTION GROUP AS DEFINED BY (FIRTH ET AL., 2007) FOR THE FIRST YEAR OF MONITORING IN THE STUDY. REPRINTED WITH PERMISSION FROM COPYRIGHT HOLDER.

A study of a site in Elmswell, Suffolk in 2009 had similar conclusions – the area-normalised energy use from each EcoHomes Excellent property has a large (400%) range – the majority from unregulated electricity use.

Survey respondents didn't feel confident that they could reduce their energy consumption further; the majority of tenants could see no way of economising their heating energy use, and felt they used the "minimum necessary". This perspective only highlights the link between behaviour patterns, or lifestyle, and consumption. Heat cannot be seen, only felt, and the long delay in feedback between use and cost serves to reduce an individual's sense of responsibility, and externalises control. The system was hindered by the lack of solidarity, in a local and a wider sense among the general public, since conservation was not always perceived as a collective effort.

While some studies have concentrated on occupant energy behaviour in a domestic setting, as introduced previously, there have been few studies which focus on low-income households, and those at risk of fuel poverty. Wood and Newborough state that while behavioural change is understood to be a large wedge of energy saving potential, the difficulty in capturing the wide ranging attitudes, understanding and abilities of users presented a major barrier to change (Wood & Newborough, 2003). An approach like that taken by *Firth et al.* (among others) is unlikely to shed light on the reasons behind this variety of occupant behaviour, or on how the attitudes of the energy consumers relates to the end energy use, because it is limited to quantitative analysis, and does not include qualitative data collection, which is required to begin to understand the reasons *why* the measured energy usage is what it is.

To do this literature from the social sciences is referred to, where there has been a lot of work into attitudes, intentions and behaviours across a very wide variety of fields, from evaluation of anti-smoking campaigns (Brown & Smith, 2007) to the social impacts of commercial mergers (Terry, Carey, & Callan, 2001).

In 1977 Lipsey defined a framework of social factors affecting energy-use:

- Personal predisposition
- Ability to carry out energy conserving practices
- Motivation to carry out energy conserving practices
- The facilitation of such behaviours by external factors

In 1980 Ajzen developed the Theory of Reasoned Action (TRA), which is a model for the prediction of behavioural intention. This was the first time behavioural intention was treated separately from behaviour in a theoretical framework, born of frustration with weak correlations found between attitude and behaviour (Hale, Householder, & Greene, 2003).

In 1985 Ajzen then went on to revised and extend TRA the Theory of Planned Behaviour, an *attitude theory* which is underpinned by a similar thinking to Lipsey's proposal, that has gone on to become widely used and accepted throughout the social sciences. In parallel to this, *applied behavioural analysis* is influenced by learning theories such as operant conditioning; this approach uses a reward/punishment system to determine behaviour. Such an approach was shown to be successful in the short term, but the tendency for individuals' behaviour to fall back into pre-intervention levels once the reward/punishment system is revoked (Lehman & Geller, 2004; Vining & Ebreo, 2002a).

A lack of correlation or consistency between general environmental concern, and pro-environmental behaviours has led to more researchers turning to attitude-behaviour models such as the Theory of Planned Behaviour, discussed in the following Section.

In 2013 the IEA launched the Preparation phase of Annex 66 – a multidisciplinary body formed of participants from 24 countries and 57 organisations (IEA-EBC, 2013). The goal of the project is to identify, describe and classify occupant behaviour, and use these to implement occupant behaviour models within thermal simulation tools. Five major sub-tasks are set to research these themes between 2014 and 2016, with

Reporting scheduled for 2017. Such an international concerted effort holds promise of a leap in our understanding of these matters.

1.8 The Theory of Planned Behaviour

Behaviour is defined, in the context of this work, as the activity of a person in response to a number of complex interactions with internal and external factors; factors including habitual, contextual, attitudinal, moral, normative and social factors. Resulting measurable outputs of this behaviour are heating use, electricity use, and water use.

Many behavioural theories and models have been developed within the field of psychological research, each with their own successes and limitations. There are so many theories and models due to a number of reasons, a few of which are discussed below:

- *The qualitative nature of behaviour* – subjective and qualitative factors contribute to any behaviour, and such items are difficult to measure explicitly. Therefore judgements must be made on the relative importance and relevance of certain factors affecting the study, to simplify models.
- *The wide range of behaviour* – There are many behaviours of interest to researchers even within a domestic setting, from car-use to grooming. There is rarely an assurance that any two behaviours share contributing factors, and if there is evidence for this, the contribution of each must be carefully weighted.
- *The complexity and interrelation of behaviours* – a high environmental attitude does not necessarily correspond to a low energy use, as Gill *et al.* find in a study of low-energy social housing at Elmswell (Gill et al., 2010). In fact the socio-demographic group most associated with positive environmental attitudes also tend to have more economic freedom and desire for energy consuming appliances, as seen in Gatersleben *et al.* (Gatersleben, Steg, & Vlek, 2002).
- *The differing research objectives* – some theories are formulated to help guide understanding of behaviours, whereas others are designed for behavioural intervention, therefore an inconsistency in purpose leads to overlapping/surplus studies.

Ajzen's Theory of Planned Behaviour (Ajzen et al., 1980) is one of the most widely applied social behavioural theories, having been implemented in the study of a variety of fields, including medical/heath, recycling, and consumer behaviour (Ajzen, 2011; Cheung, Chan, & Wong, 1999; Tonglet, Phillips, & Read, 2004). The theory itself has been able to predict certain intentional behaviours given the right conditions, dependent on three interrelated variables as shown in Figure 1.11. This means with knowledge of attitude, subjective norm and perceived behavioural control, the behavioural intention and therefore behaviour can be predicted.

Using a set of qualitative indicators which include attitude towards behaviour, subjective norm, and perceived behavioural control, one can predict the likelihood of a behavioural intention, and resulting behaviour. A methodology for this is discussed in Section 2.3.

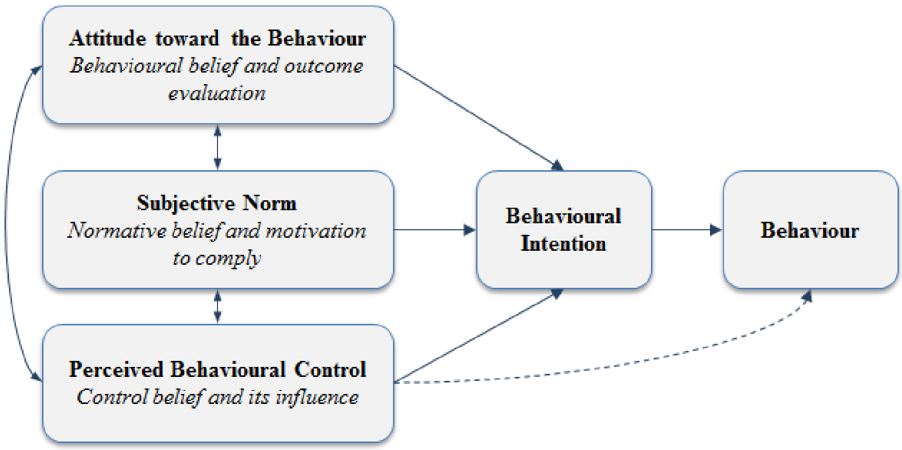

FIGURE 1.11 - THE THEORY OF PLANNED BEHAVIOUR. ADAPTED FROM (Ajzen et al., 1980).

1.9 Modelling the Built Environment

Part 1 has introduced the important aspects of occupant-impact on the in-use performance of buildings. This section explores some of the key concepts behind the modelling software used. It is important to understand the capability and limitations of the software at our disposal, rather than trust a 'black-box' model without a full grasp of how it is representing various physical mechanisms.

A Brief History

As building design has evolved into more complex forms along with more complex technologies, there has been a change in attempts to simulate and model the dynamics of energy flows in buildings. From initial models using 'steady-state' approximations, to full dynamic surface and zone models; building simulation is now a key tool for making important design decisions at all stages of the construction process, and of particular importance in 'high-performance' building design.

Engineers throughout the early decades of energy modelling will be familiar with checking tables and curves published in periodicals to inform judgement of anticipated heating and cooling loads. These were useful for quick reference, but limited in diversity of application.

Steady state modelling of building conditions using calculator tools were developed post WWII, initially reliant on the response-factor method for checking instantaneous heat gain through walls and roofs, however when time variation in the environment began to be taken into account, steady-state modelling failed to properly represent conditions; weather variations bring about significant diurnal and annual changes in temperature, wind speed, incident radiation, etc. Additionally the building usage varies with occupant schedules being dependent on the working week, local holidays, and cultural living & working patterns. For further reading on this period of energy simulation refer to an informative summary on the subject by Oh, and an excellent and personal lecture by Kusuda (Kusuda, 1999; Oh, 2013).

Early dynamic modelling techniques usually would involve breaking a building down into 'nodes', where energy flows between each node as seen in Figure 1.12. This is analogous to an electrical network each node at a particular temperature (voltage) and heat flow between the nodes (current), with the rate of transfer dependent on the thermal resistance (electrical resistance). The number of nodes corresponds to the objectives of the analysis; therefore an early design-stage simulation of heat loads will require fewer nodes than a detailed study of internal airflow mechanisms.

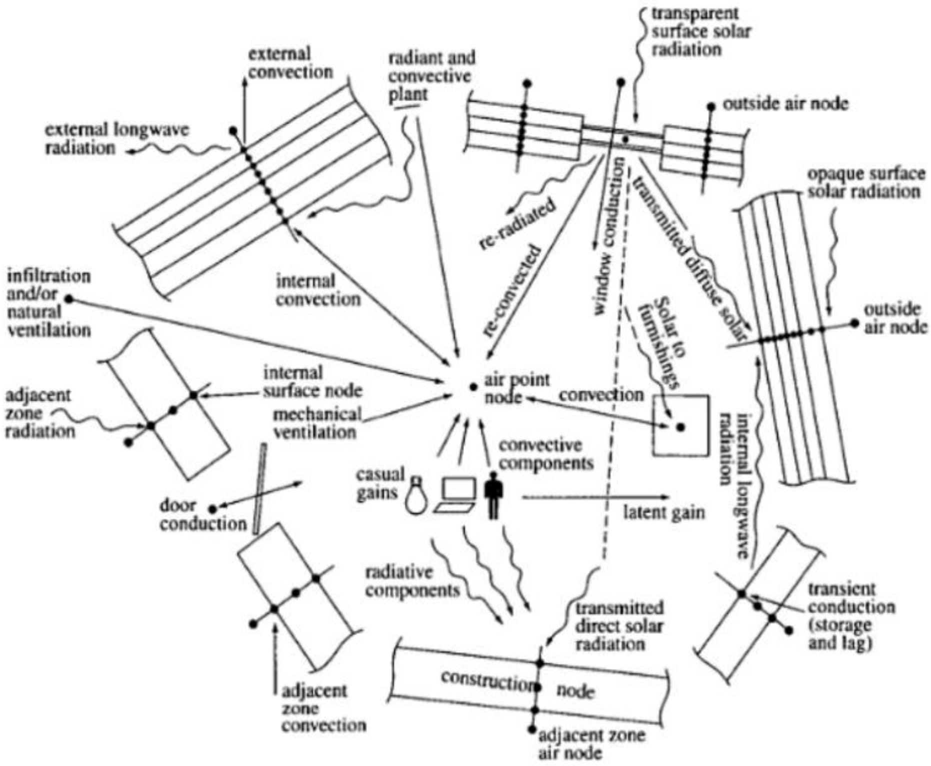

FIGURE 1.12 – AN ILLUSTRATIVE MODELLER'S PERSPECTIVE OF ENERGY FLOW IN BUILDINGS[3].

As more powerful computing devices in our research institutions have been adopted, dynamic models of buildings have begun to gather recognition. Such models use equations of heat and mass transfer, avoiding many of the assumptions and approximations used in steady-state models. Now one is able to take into account detailed occupancy schedules and internal gains patterns, high-resolution weather data, and heat stored thermal mass. The added dynamic calculations are giving crucial insight into the thermal response & behaviour of buildings, the downside to this being that the high level of inputs called for can include assumptions which do not reflect reality, and therefore 'more accurate' dynamic forecasts become redundant.

3 Reprinted from (Clarke, 2001), Copyright (2008), with permission from Taylor & Francis.

The development of building modelling software is succinctly described by Clarke (Clarke, 2001), and more recently revisited by Ramallo (Ramallo-Gonzalez, 2013), as shown in Table 1.2. In the end, the user must decide what questions they wish their building model to answer, and balance this with regards to time and cost; in many cases steady-state models would be wholly appropriate, and in other cases a more complex dynamic approach will be required.

In the past 15 years building simulations software has greatly improved, but not in these base calculations it is performing,. Instead software has become easier to use, and more integrated to other relevant calculations such as HVAC simulation, lighting and costing. In addition developments in parallel- and cloud-computation have allowed for faster and/or more complex models to be built and run at far less expense. Software such as Sefaira is a good example of a new generation of 'lite' simulation engines which use cloud processing to perform simulations and comparisons to benchmark buildings for contextualised results.

The industry is currently seeing a move toward Building Information Modelling (BIM) based workflows, whereby a the design of a building takes the form of a database, stored in one place and accessed from many. Energy simulation software is beginning to offer information exchange using formats such as gbXML, and software such as Autodesk Revit is anticipated to be the source of geometry and systems design in the near future.

TABLE 1.2 - BUILDING ENERGY SIMULATOR GENERATIONS EXPLAINED, FROM (RAMALLO-GONZALEZ, 2013).

Generation	Period	Characteristics	Example	Comment
1st	Pre-70s	• Handbook/table oriented • Simplified and gradual • Familiar to practitioners	• ASHRAE curves & tables	• User-friendly • Difficult to describe non-standard conditions • Non-integrative • Limited application • Deficiencies hidden
2nd	1970s	• Building dynamics stressed • Less-simplified • Based on standard theories	• NECAP (The Post Office) • NBSLD (National Bureau of Standards)	• Larger applicability • *Grey-box* tool for practitioners
3rd	1980s	• Field problem approach • Shift to numerical methods • Integrated modelling stressed • Graphical interface • Partial cross-compatibility	• TRNSYS (University of Wisconsin) • Energy+ (Department of Energy)	• Increased integrity • Loss of user perception / *black box* problem
4th	Post-90s	• Intelligent knowledge base • Integrated / cross-compatibility • Diverse range of application	• Virtual Environment (Integrated Environmental Solutions) • Tas (Environmental Design Solutions Ltd)	• Deficiencies overt • Easy-to-use and interpret • Predictive and multi-variate • Accessible • *Black box* effect for non-proficient users

IES VE ApacheSim

Integrated Environmental Solutions Apache software is the key thermal engine used for simulations in this thesis, and therefore requires some critical review. The thermal component of the IES Virtual Environment toolkit, Apache, is a group of component modules that form the basis for most simulations within IES VE. ApacheSim is a dynamic thermal simulation tool, using mathematical principles to calculate the heat transfer processes in and around a building. The program achieves Dynamic Simulation Model accreditation required by UK Building Regulations, and with customers including AECOM, Arup, Atkins, BDP, BuroHappold, Foster+Partners, Gensler, Ramboll, and WSP it is one of the most widely-used thermal modelling tools by engineers in the UK.

The core engine was developed in the 1980s as ESP-r software, led by Clarke in the ABACUS group at Strathclyde University. IES was a commercial spin-out from the university, headed by McLean[4]. After a 'fragile' release in 1994, the software faced a battle to by 2004 the company had grown to become a leader in the field of building modelling in the UK and in Europe.

Node-based modelling of buildings means that conduction, convection, and radiation heat transfer processes are modelled for a node at each surface of the zone individually, integrating internal heat gains, air exchanges, and plant interaction. Therefore there is no volume-based calculations in ApacheSim, rooms are considered as perfectly homogenised volumes of air, since the program is not attempting a full discrete finite volume method such as computational fluid dynamics. The dynamic simulation of a building requires appropriate weather data to define external conditions, typically hourly.

A review of the key calculation principles used in IES VE ApacheSim are found in Appendix A.

Weather

The local weather around our building has an obvious effect on the thermal and hygroscopic building conditions, along with the amount of airborne pollutants. When simulating a building, there are generally two aims:

[4] http://www.esru.strath.ac.uk/Programs/ESP-r_tut/history.htm accessed June 2015

To assess the in-use cost of the building, for which one requires 'typical' local weather conditions. This may be repeated with altered weather data for consideration of present and future climate considerations.

To check the response of the building under a range of extreme conditions which are likely to occur with some regularity over the building's lifespan e.g. under a deep cold spell, or a summer heat-wave.

There are thousands of weather stations around the UK alone, though each station does not measure all of the necessary data for the creation of a weather file, generally only a subset of the variables seen in Table 1.3.

TABLE 1.3 - REQUIRED WEATHER PARAMETERS (CLARKE, 2001)

Dry bulb temperature (°C)
Wet bulb temperature (°C)
Wind speed (ms^{-1})
Wind direction (° from north)
Atmospheric pressure (bar)
Net longwave radiation (Wm^{-2})
Precipitation (mm)
Global horizontal solar radiation (Wm^{-2})
Diffuse horizontal solar radiation (Wm^{-2})
where radiation data is not available:
Cloud cover and type (%,-)
Sunshine hours (hr)

Many agencies and institutions are creating weather files for different purposes. Typical Meteorological Year (TMY) datasets in the USA and Test Reference Year (TRY) datasets in Europe are typically used formats of hourly weather data used for building simulation. These are generated using compiled mean-monthly data from long-term historic records, and as such, are representative of typical conditions, rather than aiming to reflect any extreme weather. To represent extreme weather years, which are useful for worst-case design conditions, there are a number of methodologies. As an example, to analyse overheating CIBSE uses a Design Summer Year. This is an actual measured weather year from the mid-upper quartile of a dataset sorted by average Apr-Sept dry-bulb temperature, i.e. given 20 years of weather data, the DSY would be the 3rd hottest year.

In Europe, Meteonorm uses interpolation techniques to generate weather files for any location (MeteoTest, 2013). For UK climates, the University of Exeter has released a number of sub-hourly weather files representing future climates, generated using

UKCP09 weather generator under the PROMETHEUS Project (Centre for Energy and the Environment, 2010).

Literature Review Summary

It has been established that a Post-Kyoto Protocol reduction of CO_2 equivalent emissions to achieve an atmospheric concentration of <350ppm is a crucial requirement for avoiding catastrophic climate change. Over 50% of these emissions are shown to be attributable to the built environment, and half of this amount is from the domestic sector.

Building regulation in the UK is pushing designers to achieve ever more efficient buildings, with a current minimum standard buildings emitting over 50% less CO_2 over the standard 10 years ago. While this is a good precedent, there are still plenty of efficiencies to be made using good design techniques both active and passive to achieve carbon and energy savings beyond that of the minimum standards – evidenced in the energy/carbon related credits in certifications such as US Green Building Council's LEED, the Abu Dhabi Urban Planning Council's Estidama framework, and the Passivhaus Institute's Passivhaus energy & comfort certification, to name a few.

While design and construction of low- and net zero-carbon buildings are common, it has been discussed that the measured in-use performance is regularly very different from the expected design performance. Projects such as PROBE, Soft Landings, and CarbonBuzz have specifically targeted this effect. The measured energy performance gap has been shown to be attributable to a number of factors including:

- construction ≠ design
- simulation ≠ design
- simulation ≠ use
- use ≠ design.

This thesis focuses on the final point – design and use are siloed processes (often with relatively little in common) therefore simulations of energy use lose credibility or weight and a certificate of low-energy design becomes less meaningful.

Studies such as those by Gill et al, Socolow, and PHI show a great diversity in building energy performance even when normalised by physical and environmental characteristics (Gill et al., 2011; Schnieders, 2003; Socolow, 1978). This diversity is attributed to a number of behavioural determinants by Gill (Gill et al., 2010), including among others environmental attitude, concern, and intention; convenience; feedback and perceptions.

Hence, the behaviour of occupants is well understood to influence domestic energy use, however there have been no studies found which attempt to break down the impact of individual behavioural characteristics. It is proposed that the Theory of Planned Behaviour is tested in this context, since one can study both the hypothesised determinants of behaviour and the outcome. The following sections go on to describe what work was undertaken by the author with the aim of addressing this.

Part 2 Methodology

The second part of this thesis leads the reader through method development based on the literature review undertaken in Part 1. Since a major aspect of the design-performance energy gap discussed previously is attributed to occupant behaviour, a study is developed to further understanding of its impact on energy use.

A third-party tool for generating stochastic electric use profiles is modified to output annual profiles for occupancy, lighting and appliance usage (Richardson, Thomson, Infield, & Clifford, 2010). In addition, door-opening profiles are created based on occupancy changes, and heating thermostatic set-points are generated based on measured data in Passivhaus buildings using data from the CEPHEUS Project (Schnieders, 2003).

Passivhaus dwellings were chosen as the building type as the low heating energy requirement allows for the base-load of heating energy requirements to be met by incidental heat gains in a mid-European climate, due to very low infiltration rate and high insulation levels. A set of Passivhaus terraces are modelled in the Passivhaus Planning Package (PHPP) and IES VE using the occupancy profiles generated.

Another aspect of the work discussed in this section focuses on the development of a suitable survey to assess impact of attitude on environmental behaviour, based on the theory of planned behaviour. A study is detailed in two distinct phases: Phase 1 of the survey is intended to be carried out before the occupants move into their new Passivhaus housing, and Phase 2, which is intended to be carried out at least one year after living in the new homes. The full surveys are included in the Appendix to this thesis for reference.

Within this thesis the terms verification and calibration are used. Each term has a distinct technical meaning, and for clarity these are stated now. Verification is used to describe a procedure which establishes the validity of another methodology, procedure, or result. Calibration is a procedure whereby a calculation methodology is influenced to give results equivalent to some known/validated results.

2.1 Modelling Occupant Behaviour

It is clear from Part 1 that a better understanding of the effect of occupant behaviour would be beneficial to those involved in the design of homes or of energy policy. In this section, a method for generation of a representation of occupant behaviour is developed and tested against measured data.

Measuring occupant behaviours is a difficult task, with a great deal of monitoring equipment and analysis required, along with data collection through surveys and journals required to gain a picture of energy use in the home. On the other hand, simulation of occupancy is comparatively straightforward – use a robust methodology to represent the behaviours of occupants and its impact on the energy use of a home, then compare to measured datasets and validate results. While not a simple task, the format is a far cheaper one, with less inherent risk than extensive monitoring.

While there are many variables that can be used to inform an estimation of the energy-use within a home, it is clear one needs to limit the scope of any effort to do so to manageable and effective levels. There have been several models focusing on various aspects of household behaviour, notably: occupancy (Page, Robinson, Morel, & Scartezzini, 2008; Richardson et al., 2008); thermal comfort (Becker & Paciuk, 2009; Dear & Brager, 2002; Treeck, Frisch, Egger, & Rank, 2009); lighting (Richardson, Thomson, Infield, & Delahunty, 2009; Stokes, Rylatt, & Lomas, 2004; Widén, Nilsson, & Wäckelgård, 2009); appliance use (Richardson, Thomson, et al., 2010; Widén & Wäckelgård, 2010); and window use (Andersen, Toftum, Andersen, & Olesen, 2009a; Manu & Rawal, 2009). In this section the methods used historically are reviewed, and the parameters used in this thesis are defined.

Stochastic Models

A stochastic variable is one that randomly alters with time in such a way that the values it takes cannot be determined at each time step, but only given a probability of occupying a particular state after a large number of measurements. In fact any variable which has an unknown or seemingly randomised evolution through time can be treated as a stochastic variable. Examples could be the number of cars using a road over a given hour, the number of riders on a rollercoaster per ride, or the value of a bond on the stock market at the end of every day – in each case one is interested in determining what patterns or statistical properties are behind the on-going process.

The statistical properties of the variable are generally guessed or 'fitted' to the data, based on the analysis methods available, then tested against 'verification data', which is ideally different to the data used to design the model.

"White-box" models vs. "black-box" models

There are two distinct ways to go about building a model of a stochastic process. The "black-box" model only uses the output of the process as the basis for the statistical analysis, and hence brings no bias or assumption to the process. A "white-box" model on the other hand is the result of employing knowledge about the output's dependence on certain variables; the process may remain stochastic, but its behaviour will be dependent on other factors, which are known or can be modelled. For example, a rollercoaster's occupancy may peak during school holidays and weekends, therefore its form can be proposed to be dependent on the date.

Though both approaches have their merits, in our case a useful model needs to have real dependencies that can be visualised and understood, for this reason a "white-box" approach is utilised wherever possible.

Simulating occupant presence

Being present within a building is a necessity for occupant interaction with a building, and is therefore a fundamental input to all other models of occupant behaviour. Each person present will emit heat, water vapour, and carbon dioxide, among other pollutants, and will arrive with a set of thermal comfort conditions. In a residential setting, an occupant may use appliances, and consume hot and cold water; alongside consumption, occupants generate solid and liquid waste. Any neighbourhood schemes for generating all or part of the resources consumed within an area of housing will also need to know the timings and scales of the various loads considered to optimise the size, control, and networking of plants and auxiliary equipment.

Some of the influences which occupants have on the buildings they occupy are listed below, as discussed in (Robinson, 2006).

- Control of HVAC systems
- Use of windows and doors with associated ventilation rates and heat losses
- Position of blinds
- Production of metabolic sensible & latent heat, and radiation

- Use of appliances with associated electricity and water consumption, internal heat gains and production of grey and waste water
- Use of artificial lighting
- Emission of pollutants including CO_2

A constructional approach to modelling some aspect of a space (e.g. thermal properties), while plausible, would be very arduous indeed. A stochastic approach, however, may capture the intricacies involved to a point, without needing a vast density of data.

To account for changes in occupancy, one must exclude any static representations of persons or appliances in a space. The gains should vary to represent actual usage over time, rather than a steady-state analysis (though such an analysis is very useful for sizing of equipment, it has no place in an operational model!). A common way to simulate occupant presence in a building is to use a simplified representative profile that is mainly dependant on the type and size of building, such as those used in UK Building Regulation (see National Calculation Method profiles). Such a profile may change at weekends and during holiday periods, and represents the same usage and behaviour throughout the timeframe being modelled.

Forecasting occupancy

It was Hunt who originally highlighted the importance of occupant interaction with lighting appliances (Hunt, 1980), later Newsham and Reinhart introduced a stochastic model of presence in the Lightswitch model (Reinhart, 2004). Lightswitch stochastically generated occupancy patterns for each worker in an office given that the workers arrived within ±15 minutes of 9am, took lunch breaks around 1pm, and had a 50% chance of also taking a coffee break. This was an original piece of work in that it set the scene for a whole array of occupancy models that followed.

In 1994 Capasso *et al.* (Capasso, Grattieri, Lamedica, & Prudenzi, 1994) was the first to use stochastic techniques to model occupant activity and appliance use in the home. Time-use survey data was implemented to estimate occupancy and probability of appliance usage. Capasso used an Italian time-use survey from 1989, and in the following work the UK Time Use Survey (TUS) conducted in 2000 was used. These journals indicated which major and minor activities a person was performing at a 10 min resolution throughout the day, and they also included a specified household location of the activity and indicated whether the activity was undertaken with anyone else.

In the UK Time Use Survey, 21,000 such weekly journals were collected from over 5,000 households in a longitudinal study by Ipsos-RSL (Ipsos-RSL, 2000). Figure 2.1 shows fifty such examples of active occupancy from the data set. As expected, most of the activity happens in the evening, between 16:00 and 23:00. This is probably when occupants arrive home from work and school, and spend time in the home. This correlates to the average domestic energy demand profiles, therefore adding further weight to the idea that home energy use is closely dependent on occupant activity within the home, as postulated by Yao and Steemers (Yao & Steemers, 2005), among others. While variability is obvious from person to person, the night-time inactivity pattern tends to be similar in 90% of cases, and the daytime is a short concentration of activity between 07:00 – 09:00 then another more reliable concentration 18:00 – 23:00. This is representative of a 09:00 - 05:00 working pattern. One must be wary that while the majority of people work during the day, it should not be assumed all of the inactivity during the night is due to sleeping as some persons may work night shifts.

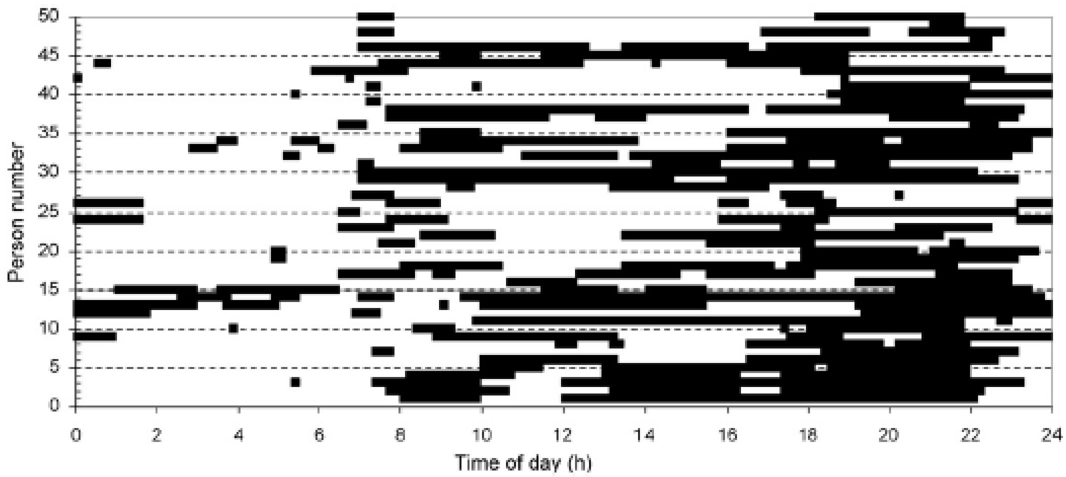

FIGURE 2.1 – FIFTY EXAMPLE ACTIVE RESIDENTIAL OCCUPANCY PROFILES AS REPORTED IN TUS (TIME USE SURVEY).[5]

More recently a number of studies, notably (Richardson, Thomson, et al., 2010; Widén & Wäckelgård, 2010), have followed a similar method to Capasso, and used

5 Reprinted from (Richardson et al., 2008), Copyright (2008), with permission from Elsevier.

similar local time-use data as the basis for behavioural representation. When combined with an approximation of electrical appliances present, and the electricity demand of each appliance, these three components provide an understanding of electricity demand.

To generate synthetic occupancy patterns, Widen and Richardson use the statistics gleaned from the respective time-use surveys, and build a Markov Chain method to generate stochastic occupancy profiles. This method is described in the following section.

Markov-Chains

The Markov-Chain technique is an established stochastic method for generating data for a system with a discrete number of possible states. A first-order Markov-chain means that the state of a system is dependent only on the previous state, not on any other information (Gilks, Richardson, & Spiegelhalter, 1995).

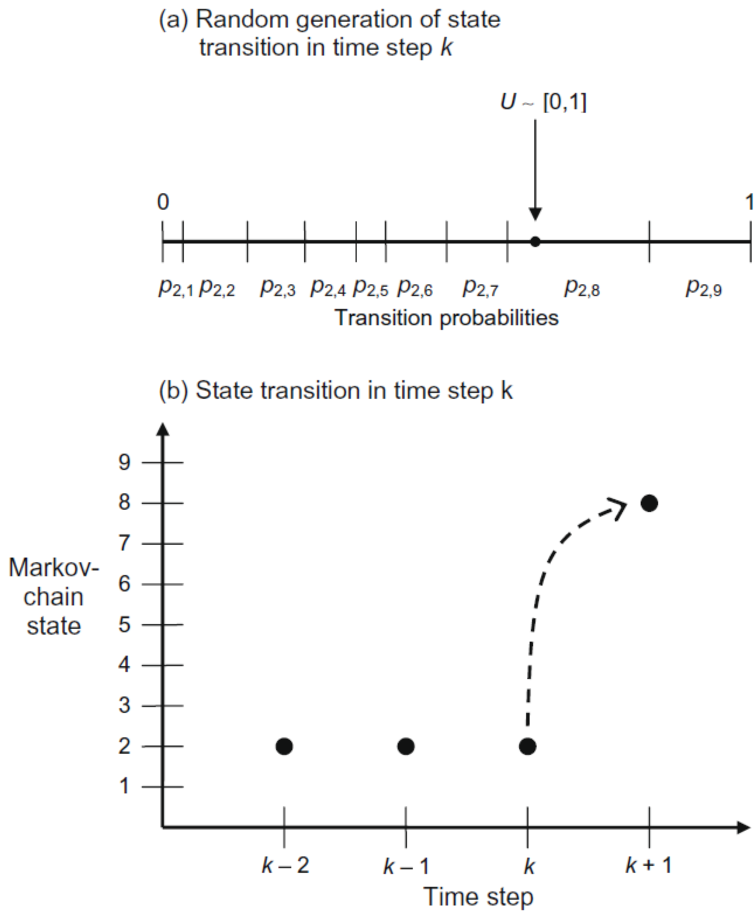

FIGURE 2.2 - GENERATION OF SYNTHETIC ACTIVITY SEQUENCES IN THE MARKOV-CHAIN MODEL. (A) SHOWS HOW A UNIFORM RANDOM NUMBER IS USED TO DETERMINE THE TRANSITION PROBABILITY TAKING PLACE IN (B) BETWEEN TIME STEPS *K* AND *K + 1*[6].

The stochastic Markov Method of data generation is an established technique for systems based on a discrete number of states and is used in fields such as data mining, machine learning, Bayesian methods, and biological genetic research, to name but a few.

Figure 2.2 shows a representation of generating synthetic activity sequences in a simple Markov chain model. There is some probability $p_{ij}(k)$ which governs the switching from time step k to $k+1$ and for all states of k there is defined a transition probability matrix. The diurnal fluctuations in occupancy and activity profiles are represented by the variation in transition probability with respect to each state. The

[6] Reprinted from (Widén & Wäckelgård, 2010), Copyright (2010), with permission from Elsevier.

Markov chain is then non-homogeneous as compared to homogeneous processes with fixed transition probabilities.

To get from TUS data to transition probability estimates is a fairly simple process. Supposing N persons were represented by a series of TU data, giving which of 8 different activities is taking place at every time-step $k = 1, \dots, N_k$. For each person N the probability of a transition to each other state is calculated by

$$\boldsymbol{p_{ij}(k)} = \frac{\boldsymbol{n_{ij}(k)}}{\boldsymbol{n_i(k)}} \tag{2.1}$$

Where $n_{ij}(k)$ and $n_i(k)$ refer to the number of people in state i moving to state j at timestep $k+1$ and the number of people staying in state i at timestep $k+1$, respectively. Different states refer to different activities in this case. In the case of missing TUS data in certain places, there would be a division by zero and the equation could not be calculated. For this reason the average over a larger interval may be used:

$$\boldsymbol{p_{ij}(k)} = \frac{\boldsymbol{\Sigma_{\tau=a}^{b} n_{ij}(\tau)}}{\boldsymbol{\Sigma_{\tau=a}^{b} n_i(\tau)}} \tag{2.2}$$

Where a and b refer to more distant timestep leaps, τ. The representation of occupancy in the model provides the primary method for creating synthetic electricity demand data with appropriate aggregate daily profiles. This technique for generating occupancy profiles uses a ten-minute grid of the current states together with the probability of an occupancy state change at the boundary to calculate whether a change of state occurs in the next period (Richardson et al., 2008). In the example given in Table 2.1.

it is clear that if a two-person house is unoccupied (the number of active occupants = 0) at 21:00 then there is an 89.2% chance the house will still be unoccupied at 21:10. Ten minutes later there will be a similar though slightly altered situation, and in this fashion 144 transition probability matrices are defined to establish transition probabilities for a full day. Such occupancy data is demonstrated by Richardson *et al.* to represent the measured behaviour of households well (Richardson et al., 2008).

TABLE 2.1. EXAMPLE TRANSITION PROBABILITY MATRIX FOR A TWO-PERSON HOUSEHOLD ON WEEKDAYS, INCLUDING ACTIVITY PROBABILITY (RICHARDSON, THOMPSON, & INFIELD, 2010).

Number of active occupants	Next state (at 21:10) 0	1	2
Current state (at 21:00)			
0	0.892	0.082	0.025
1	0.038	0.878	0.084
2	0.003	0.043	0.954

Verification 1: Individual house occupancy simulation

Figure 2.3 shows four days' of generated occupancy profiles. The nature of stochastic profiles means each is different, though similarities are apparent between them. The trend is for some activity in the morning between 07:00 - 09:00, and the majority of occupancy in the evening. Looking at a journal entry for a single day, it is clear that the general trend is followed. The Markov chain seems to adequately represent a day when compared to the TUS data from which it was taken.

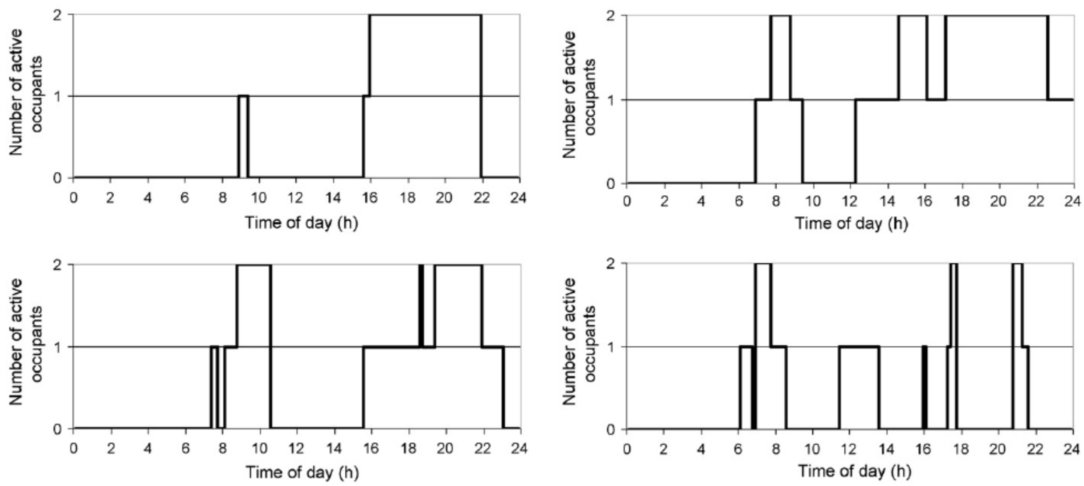

FIGURE 2.3 – FOUR EXAMPLE PROFILES GENERATED BY THE CREST MODEL (TWO-PERSON HOUSEHOLD, WEEKDAY)

Verification 2: – Aggregate profiles

If one compares a number of stochastically generated profiles to the TUS average, there will also be a very close match, as Figure 2.4 shows. The measured data is taken from 2,000 measured 2-person households, while the simulation data is the average of 10,000 2-person household simulations, each at weekdays and weekends.

Widen et al. use a similar method using Swedish TUS data to generate representative occupancy behaviour for applications concerning lighting use in the home (Widén et al., 2009).

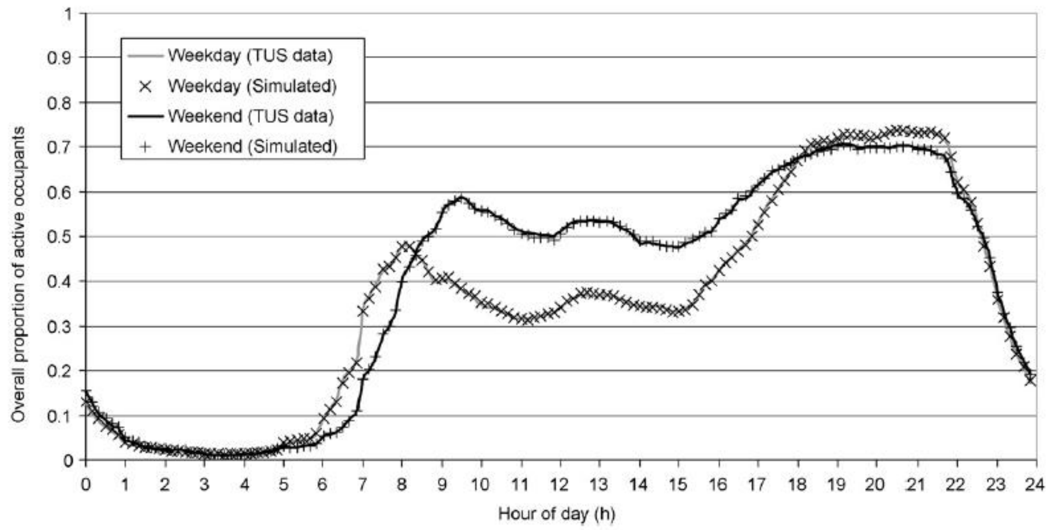

FIGURE 2.4 – AGGREGATED PROFILES COMPARED SIDE-BY-SIDE. (RICHARDSON ET AL., 2008)[7]

Now that occupancy patterns and their impact on buildings have been considered in the previous section, impact of appliances in the home are considered, and the various ways to model ownership of such appliances is reviewed. The appliances used within domestic appliance models are the building blocks of a 'bottom-up' building stock model. Capasso is cited with the some of the earliest work on building an appliance-based bottom-up model (Capasso et al., 1994) which, like the majority of such research, was grounded in a Demand Side Modelling (DSM) approach, for informing domestic grid demand. Later others used similar means for both DSM and thermal modelling approaches (Stokes et al., 2004; Widén & Wäckelgård, 2010; Yao & Steemers, 2005).

In these works each household appliance is given a probability of ownership, an associated power cycle, and some probability of a cycle initiating. The cycle is either a constant power load for a set period, or in the more complex models, a variable load changing at discrete intervals until the defined cycle is complete. Each of these factors will be briefly explored in the following section.

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7 Reprinted from (Richardson et al., 2008), Copyright (2008), with permission from Elsevier.

Ownership of appliances

Of course, one is not prescribed a particular set of appliances for all households; each property has an ever-changing combination of electrical items, depending on complex social and economic factors It is very difficult to get true details about complete appliance ownership, in modern society devices are exchanged and updated frequently, so for practical purposes, each major domestic appliance type has an associated probability of ownership. Since in our project concerns modern low-energy housing, the assumption is made that no additional heating appliances will be used within the home. Table 2.2 shows the proportions of households with each appliance listed, modified from (Richardson, Thompson, et al., 2010)

The use of appliances is never a constant factor, and the only real useful way to model the use of household appliances is through a statistical or archetypal approach. Due to the shifting nature of electronic appliance ownership and usage, it is erroneous to take only a snapshot of appliance use and ownership in the UK as our guide for the future, without considering the implications first.

The Department for Energy and Climate Change (DECC) has a good source of information about domestic energy use in the UK from 1970 to 2011, with the majority of information from 1990 to 2011. This resource gives a good insight into the trends in modern domestic appliance use. While the proportions of households owning appliances has greatly increased, Figure 2.5 shows that the overall energy use from domestic appliances per household has stayed at a surprisingly steady figure, in part due to the inefficient appliances adopted early on now being replaced with much more efficient ones. In fact, the trends for more environmental behaviour may have also affected the figure shown here, with more attention being spent on switching off appliances not in use, and using more efficient lighting schemes and equipment. The aggregate loads (and therefore the aggregate gains[8]) could be modelled as fairly

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[8] Arguably, a large proportion of electrical load inside the home is in fact also a heat gain inside the home. There are a number of appliances and products for which this is not the case, notably any appliances used outside of the thermal envelope (e.g. external lighting, lawnmowers), devices which heat water and therefore have a large latent heat output (cooking, washing) and appliances which have a drainage pipe through which sensible heat escapes the envelope (generally, electric showers, washing machines, etc.).

consistent over the last twenty years. The dynamic picture, on the other hand, is a different story; with the rise of personal electronic devices, digital TV, home wireless networks, and games consoles, household electricity demand is a very different picture to that seen in 1990, with more variability and intensity in demand. Figure 2.5 shows 2012 data from DECC on the standardised energy consumption per household, person, and unit disposable income from 1970 to 2011 (Department of Energy & Climate Change, 2012).

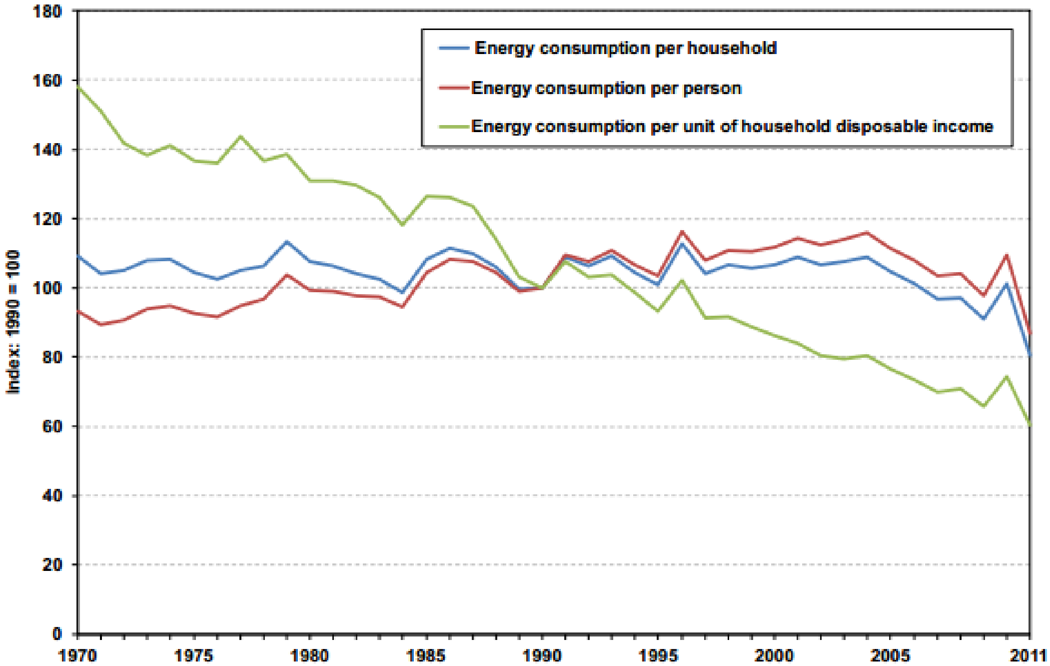

FIGURE 2.5 – ENERGY CONSUMPTION PER HOUSEHOLD, PER PERSON, AND PER UNIT OF DISPOSABLE INCOME FROM 1970-2011 (DATA FROM DECC (DEPARTMENT OF ENERGY & CLIMATE CHANGE, 2012))

Essentially, appliances that are becoming more popular and available are mostly *standby appliances*, which use a little power all the time, and a much higher amount while in use, generally while the occupant is present. The associated gains are therefore going to superimpose with the gains from the occupants themselves, leading to a negative contribution to the heating energy requirement over the winter heating season. Such usage patterns may contribute to overheating in the summer season, but this is not considered in this work.

Appliance Load Models

Appliances load types can be defined as follows: *continuous draw*, which uses a set power at all times, e.g. clock, alarm; *standby appliances*, uses a certain power when not in use, and a different power when being used, e.g. television, television receiver box; *cold appliances*, which are always in use, but cycle as varying power rates from zero to a set power level, e.g. refrigerator, freezer; *active appliances*, which are either drawing a set power or off e.g. lights, shower, electric hobs.

Depending on the appliance load type, the method for modelling the load varies. In general, there is a certain chance that a 'switch-on' event will occur and the appliance will switch on from off, or on from standby, and begin a power-cycle.

Table 2.2 Appliance cycle information is derived from various sources, including the Market Transformation Program (DEFRA, 2009) and UK Department of Energy and Climate Change factsheets (Department of Energy & Climate Change, 2012).

TABLE 2.2 – APPLIANCE OWNERSHIP ASSUMPTIONS USED IN MODEL, MODIFIED FROM (RICHARDSON, THOMPSON, ET AL., 2010) AS DESCRIBED IN TEXT.

Appliance category	Appliance type	Proportion of dwellings with appliance	Cycles per day (number)	Mean cycle length (minutes)	Mean cycle power (W)
Cold	Chest freezer	0.16	16.76	14	190
	Fridge freezer	0.65	16.76	22	190
	Refrigerator	0.43	16.76	18	110
	Upright freezer	0.29	16.76	20	155
Consumer Electronics + ICT	Cassette / CD Player	0.90	3.32	60	15
	Hi-Fi	0.90	0.30	60	100
	Iron	0.90	0.10	30	1000
	Vacuum	0.94	0.30	20	2000
	Fax	0.20	0.54	31	37
	Personal computer	0.71	1.23	300	141
	Printer	0.67	1.79	4	335
	TV 1	0.98	4.01	73	124
	TV 2	0.58	4.01	73	124
	TV 3	0.18	4.17	73	124
	VCR / DVD	0.90	4.01	73	34

Appliance category	Appliance type	Proportion of dwellings with appliance	Cycles per day (number)	Mean cycle length (minutes)	Mean cycle power (W)
	TV Receiver box	0.93	4.01	73	27
Cooking	Hob	0.46	1.15	16	2400
	Oven	0.62	0.60	27	2125
	Microwave	0.86	0.26	30	1250
	Kettle	0.98	4.16	3	2000
	Small cooking (group)	1.00	0.80	3	1000
Wet	Dish washer	0.34	0.66	60	1131
	Tumble dryer	0.42	0.33	60	2500
	Washing machine	0.78	0.54	138	406
	Washer dryer	0.15	0.54	198	792
Water heating	Electric shower	0.67	0.79	3	9000

Lighting-Use Model

Lighting is major factor to consider in simulating the energy use within most buildings. In the UK 16% of domestic energy use is attributed to lighting, one of the highest proportions found in the EU (Bertoldi & Atanasiu, 2007).

There are many influences on the use of electric lighting, including but not limited to: natural lighting levels, surface illumination, blind/curtain position, period of occupancy, and activity type; along with a host of social factors such as economic allowance, sharing of spaces, and in a domestic situation, 'cosiness' (Bladh & Krantz, 2008). There has been a great deal of work published on the use of lighting in workplaces and in a domestic setting (Capasso et al., 1994; Firth et al., 2007; Hunt, 1980; Masoso & Grobler, 2010; Reinhart & Walkenhorst, 2001; Widén et al., 2009).

In the present study the model offered by Richardson et al within their domestic energy use model has been utilised to give an approximate model of domestic lighting, based upon activity type and typical amount of daylight available (10-min resolution), ignoring room orientation and the with the implied use of blinds and curtains implicit within the statistics (Richardson et al., 2009). When determining if a light is switched on at any particular time, the method runs through a number of steps:

- The exterior irradiance levels are checked to determine if the base conditions for natural light levels are met, based on a randomised value from a normal distribution of mean 60 Wm^{-2} and variance of 10 Wm^{-2}. There is also a 5% chance a positive result regardless of the output, to account for daytime lighting usage.
- The type of lighting units within the dwelling is a weighted, e.g. percentage of halogen sets and single CFDs.
- The active occupancy in the building – a higher chance of a switch-on event occurring with higher occupancy levels.
- A final calibration is used to balance the mean energy output demand and the expected mean energy demand across the year.

At each time-step these four steps are combined to generate a probability of a switch-on event occurring. A random number is generated and if it is lower than the probability of a switch on, then the switch-on occurs. The duration of the lighting switch-on is given by another randomised sample from a probability distribution of particular lighting-use durations.

Richardson shows this lighting model to compare well to Stoke's model, validated against 100 measurements in UK dwellings (Richardson et al., 2009; Stokes et al., 2004).

2.2 Choosing a Building Template

There is some environment in which the proposed study must be based, a set of constraints on the form and features of the building. We have discussed a number of low-energy certifications and standards, including CfSH, LEED, Passivhaus, CarbonLite and Minergie.

The Passivhaus standard shows repeatable low energy requirements for space heating in a range of studies (Schnieders & Hermelink, 2006), and the base-load of heating can be met by the heat gains generated by the occupants themselves – effectively making the occupant behaviour a far bigger proportion of the picture.

It has also been shown by the DECC that Passivhaus level efficiencies must become the new standard for household efficiency fast, or we are highly unlikely to meet our long-term emission targets (DECC, 2010).

In addition, the CEPHEUS project demonstrated that the Energy Performance Gap is less apparent when building to the standard, which means less noise when comparing simulated results in the PHPP to measured results from Passivhaus dwellings, which will improve the accuracy of our comparisons in Part 3 of this thesis.

It is for these reasons that Passivhaus has been chosen as the template for the following study.

Passivhaus Planning Package (PHPP) Software

PHPP is the software developed by the Passivhaus Institute (PHI) to aid the design of Passivhaus aspiring buildings, both domestic and non-domestic, and is required to be completed for PHI to be able to certify the end-product. The tool itself is all based in an MS Excel spreadsheet, with a number of tabs for data input which must be carefully filled-out before submission for checking by the PHI, or an authorised local body such as the UK Passivhaus Trust.

PHPP is regarded as a static or semi-static simulation tool, 'semi' due to its hourly representations of overheating in summer, including solar heat gains, and its monthly representation of the external conditions. Other than solar heat gain and weather data, there is no temporal profiling of information.

The software assumes a blanket internal heat gain (IHG) value of $2.1\,W\,m^{-2}$, regardless of the size of the dwelling – giving, for example, 294 W useful sensible heat gain in a 140 m^2 four-bed dwelling, including occupant heat gains. It should be noted

DHW internal heat gains are treated separately by PHPP. It has been shown by Grant & Clarke that this figure is quite appropriate for medium and large dwellings, compared to typical assumptions used for internal heat gain calculations (Grant & Clarke, 2014). Grant and Clarke critique the static gains figure, and propose an equation to calculate a better approximation of occupancy given a certain floor area, based on occupancy data available for the UK housing stock. The resulting IHG calculation for a range of floor areas is a better representation of occupancy than a static figure, which in this case is equivalent to a house of roughly 130 m^2. To date this has not been included in PHPP software.

The limitations of a static calculation compared to a dynamic simulation are well known, a dynamic simulation can give insight to detailed varying usage profiles and weather patterns.

In Section 3.2 a modified form of PHPP is used to test a range of average occupancy and internal heat gain values to better reflect the same inputs being used in the full dynamic simulation in IES VE (discussed in this part of the thesis).

2.3 Measuring Occupant Attitude and Behaviour

How an individual's attitude and behaviours affect the energy use in a household is highlighted in the literature review as an area of research lacking data and analysis.

Exeter City Council finished the construction of 21 new social housing units in 2011, of which all would achieve Passivhaus status. Knights Place and Rowan House were designed by Gale and Snowden Architects in collaboration with Exeter City Council's Housing and Development Team (ECC), and contracted by ISG Pearce Construction. Along with the innovative 'Larch House' and 'Lime House' in Ebbw Vale, and the 'Racecourse Bungalows' in Sunderland, the Exeter Passivhaus development is among the first completed council-built Passivhaus developments in the UK (McLeod, Hopfe, & Rezgui, 2012a; Siddall, 2012b).

The developments are aimed specifically at older residents interested in down-sizing, and as such have a number of features included for compatibility with aged residents such as lifts, and a step-free design throughout, including a level wet-room for easy washing. Some more-specific details about each project follows.

Aims & Objectives

The aim of the study is to test the Theory of Planned Behaviour's ability to predict energy-related and ecological behaviours in the context of low energy housing. As per the TPB, data collected must include indicators of attitude, perceived control, and social norms to be able to predict behavioural intention. A side-objective of the study is to examine the shift in attitude toward ecological behaviours over the course of a move into low-energy housing.

Note on Social Housing

The majority of our housing is built and sold by private developers, however some of these projects are social housing projects built for council clients. Social Housing is a major part of the UK's housing infrastructure, with local authorities, housing association, and social landlords owning nearly 20% of all UK housing stock (DCLG, 2007c). There are a few differences when considering low-energy social housing compared with low-energy developments in other parts of the building stock.

Firstly, social housing is frequently occupied by those also dependent on heating grants, either the elderly who qualify for winter fuel allowance, or the financially insecure; in the latter case savings in heating use mean savings for the councils who manage them. This leads to an improved feedback loop for any investment into efficiency measures, since the financial benefits are passed on to the investor. This also has a negative impact in the case that the council tenant has a different attitude toward the energy bills of the home if they are not paying them.

Secondly, tenants of low-energy council housing are less likely to display a 'green bias', i.e. they regard their home differently to how a private tenant/buyer would, and while the private tenant/buyer may be happy to slightly alter behaviour for energy savings, the social tenant may not. This type of behaviour is explored in pre- and post-occupancy review of social Passivhaus homes in Exeter, seen in Part 1.

Rowan House

Rowan house, shown in Figure 2.6, features masonry block walls and insulated aluminium window and door frames, which are specified to the Passivhaus standard. The build comprises three units; two single bed on the ground floor, and a two-bed apartment on the 1st floor. There is an individual MVHR unit installed in each dwelling: a Genvex GE Energy 1 counter-current heat exchanger with an Optima 250 programmable controller. The heating for all dwellings is supplied via post-air heating within the ducts of the ventilation units.

FIGURE 2.6 - ROWAN HOUSE, MARKED INTO SECTIONS A, B AND C INDICATING THE EXTENT OF EACH PROPERTY BY THE DARK UNBROKEN LINE.

Rowan House was completed in late 2010 and the ground floor flats were occupied in December. The first floor flat was occupied in March, after complications for ECC with finding a suitable tenant.

Knights Place

The development in Beacon Heath is larger than Rowan House, with 18 units shared between two blocks. Each block is three storeys high and comprises of three units per storey. The site can be seen in Figure 2.7, and ground floor plans of Block 1 and Block 2 in Figure 2.8 & Figure 2.9, respectively. The construction is block masonry, with insulated timber windows and aluminium door frames, and a clay-tiled insulated roof. The materials are all specified to comply with Passivhaus standards, and the development was fully certified in 2012. Residents moved into the development in July 2011.

FIGURE 2.7 - KNIGHTS PLACE COMPRISES TWO BLOCKS OF NINE UNITS EACH, WITH THREE FLOORS IN EACH BLOCK, AND THREE FLATS PER FLOOR. THE VIEW SHOWN HERE IS THE SOUTHERN ASPECT, WITH BLOCK 1 ON THE RIGHT OF THE IMAGE AND BLOCK TWO IN THE FOREGROUND ON THE LEFT.

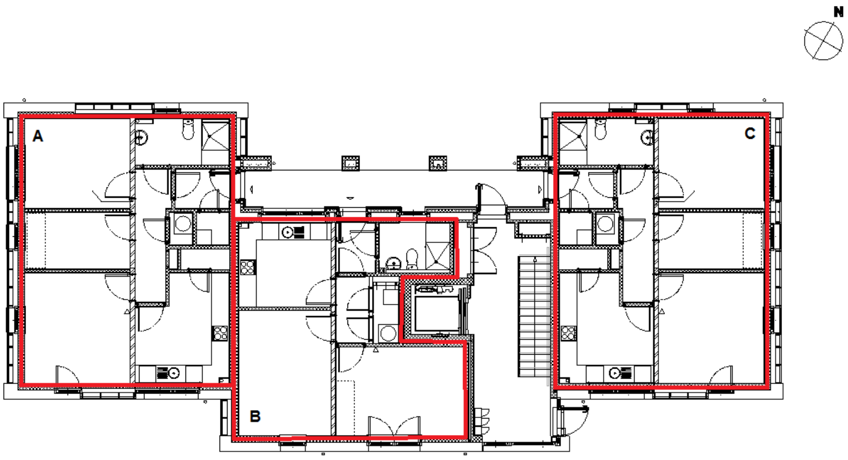

FIGURE 2.8 – GROUND FLOOR OF BLOCK 1 AT KNIGHTS PLACE, WITH THE THREE SEPARATE APARTMENTS LABELLED A, B & C. THERE ARE TWO MORE SIMILAR FLOORS ABOVE, WITH EACH FLOOR COMPRISING OF THREE SIMILAR FLATS (A & C ARE TWO-BEDROOM FLAT, B IS A SINGLE BEDROOM FLAT) AND THE COMMUNAL ENTRANCE WAY. ADAPTED FROM PLAN BY GALE & SNOWDEN ARCHITECTS.

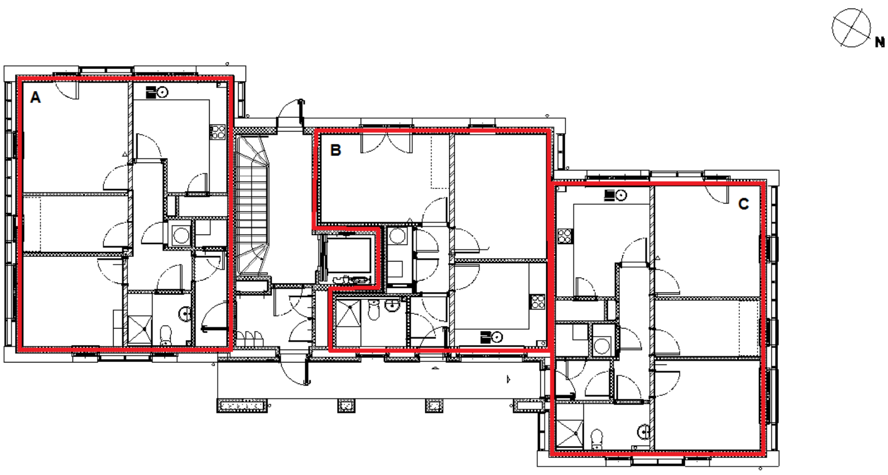

FIGURE 2.9 - GROUND FLOOR OF BLOCK 2 AT KNIGHTS PLACE. THERE ARE TWO MORE SIMILAR FLOORS ABOVE, WITH EACH FLOOR COMPRISING OF THREE FLATS (A & C ARE TWO-BEDROOM FLAT, B IS A SINGLE BEDROOM FLAT) AND THE COMMUNAL ENTRANCE WAY. ADAPTED FROM PLAN BY GALE & SNOWDEN ARCHITECTS.

Data collection methodology

Thanks to early stage involvement with the architects and the council, where the ECC Housing and Development Team were very open to academic involvement throughout the project, the opportunity to contact the potential incoming residents during the identification and initial contact stages was present.

There are a number of qualitative data collection methods and approaches that were considered at this stage, detailed below.

Survey

Established methods are well-documented, therefore plenty of guidance is available for designing effective surveys. Normally a simple and straight-forward method for gathering data on attitude, preference, values, and motives, while providing opportunities for quantification through standardisation of data. Surveys also require little to no training to collect data and allow anonymity – an important concept where sensitive areas are involved. However, surveys are susceptible to bias, both in terms of the questions themselves - which must target specific areas of study - and in the respondent - who may have any number of biases unknown to the researcher while responding.

Self-reporting of data is shown to be strongly linked to a number of factors including personality, interpretation, self-awareness, and response bias (Austin, Deary, Gibson, McGregor, & Dent, 1998).

Interview

The interview is a flexible technique that can be altered to suit different styles of session from open to structured, limited only by the skill and experience of the interviewer. Face-to-face interviews allow on-the-fly modifications and deeper probing of answers using non-verbal cues not possible with other methods of data collection. With the right circumstances and interviewer, interviews can provide rich and insightful material. On the other hand, the wrong circumstances can lead to difficult and unreliable data. Interviews also require a high level of personal intrusiveness, particularly where conducted in the interviewee's home environment, so sensitivity to the interviewee is very important.

Observation

Direct or indirect observation does not rely on the subjectivity (or memory) of the participants, and allows assessment of behaviours objectively, and is complimentary to other methods such as interviews or survey data, giving some insight into discrepancies between perceived/presented behaviour and actual. Observation leads to laborious data analysis, particularly if real-time video or audio streams are to be analysed. Additionally, the technique can be particularly intrusive, and lead to questions about subject privacy. The equipment required for indirect observation can be costly and require access to maintain (i.e. data collection/batteries).

Walkthrough Analysis

A quick and easy walkthrough requires little preparation and training, and is a flexible technique, however the quality or quantity of data available to be collected is not seen to be high in a domestic setting, and the observer is privy only to a moment in time during which the observing may have a effect on the measurement.

Unobtrusive Measures

Collection and study of data sources such as records and bills may give valuable back-up to data obtained through other means, and the nature of the inquiry is less personal – however this can lead to ethical issues when data is used without the participant's knowledge or permission. The completeness of a data set can also be an issue, e.g. bill data may be available for one participant but not for another who pays through a different means.

TABLE 2.3 – FOR AND AGAINST QUALITATIVE METHODOLOGIES - CONTEXT-SPECIFIC

Method	For	Against
Survey	+ Scientific qualification + Quantification of coded parameters + Facilitation + Relatively unobtrusive method	- Response rate may be low - Subject to bias - Greater access may be afforded to tenants - Lacks responsive quality
Interview	+ Scientific qualification + Quantification of coded parameters + Allows for probing of interesting responses – dynamic + Low resources required – microphone & notepad + Good sample size for interviewing given timeframe	- Requires some skill as an interviewer to gather good quality data - Can feel obtrusive when discussing sensitive areas (e.g. Disability, illness, hygiene)
Observation	+ Actual behaviour recorded rather than perceived/projected + Rich source of data + Flexible use potential beyond design	- Expensive equipment - Intrusive monitoring

Method	For	Against
	+ Possibility of monitoring while parallel energy and DHW monitoring taking place in the dwellings	
Walkthrough analysis	+ Flexible + Quick + Detailed	- Possibility of error - Impractical to extract useful behavioural data - Limited to a 'snapshot' in time
Unobtrusive measures	+ Unobtrusive + Quantitative	- Difficult to gather data and gain permission for use - Limited sources - Non-existent data

Arguments for and against various qualitative data collection methods are given in Table 2.3. While Observation comes out favourably, discussion with colleagues indicates that the equipment and maintenance costs were too high for the project, along with the space requirements in the house to gather acceptable data being deemed too intrusive. Interviews come out as another good route to take, as they allow for in-depth discussion of points in a flexible manner, and answers that lack quality or depth can be further probed. Due to low sample size, and high risk of failure to collect suitable data using full interview techniques, a plan for a semi-structured interview/survey technique was developed, which would combine standard survey questions which use techniques such as the Likert Scale to add quantitative aspects to the data collection, as well as to encourage discussion on any salient points with some open-ended questions.

While the measurement of attitude does not present much of an issue for a survey, measurement of behaviour is rather more difficult. Self-reporting of recycling behaviour shown to have serious inaccuracies in a study by Corral-Verdugo and Obregón-Saudo (Obregón-Saudo & Corral-Verdugo, 1997). As stated by Vining and Ebreo, there have been few studies which include a treatment of contextual references, examining differences between communities and neighbourhoods (Vining & Ebreo, 2002). Is should be noted that there is no way to be sure that presented/reported behaviours are a true representation of reality.

Survey Design

A method was thus developed which would involve surveying the residents at two stages in time, Phase 1 – before or very shortly after moving in, and Phase 2 – after at least 12 months. The methodology is shown in Figure 2.10.

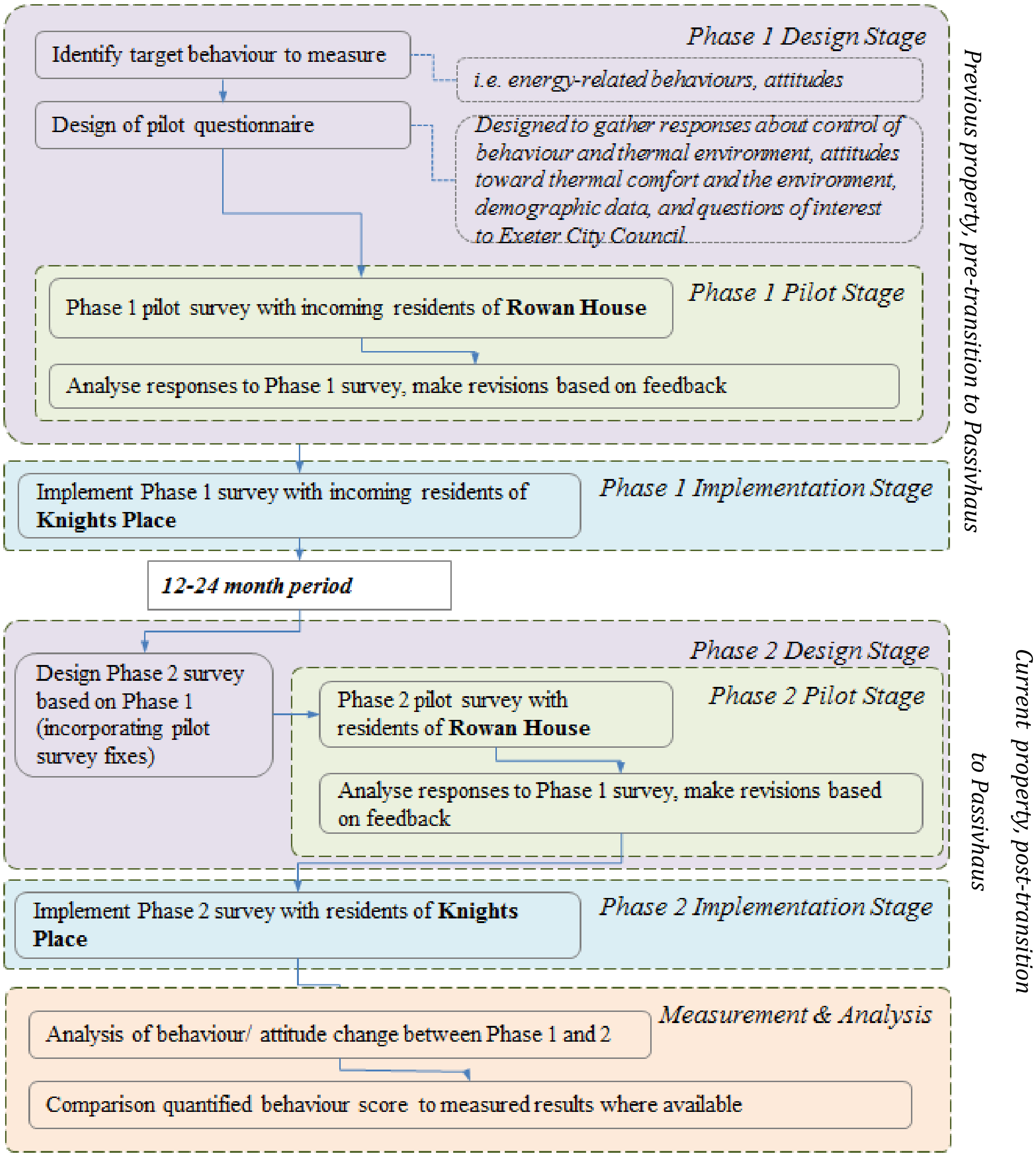

FIGURE 2.10 - SURVEY DEVELOPMENT FLOWCHART, DESCRIBING PRE-OCCUPANCY (PHASE 1) AND POST-OCCUPANCY (PHASE 2)

The surveys are comprised of three sections, each of 20 questions (a combination of closed and open-ended), designed to take 30-60 minutes to complete. A copy of the Phase 1 and Phase 2 surveys is included in full in the Appendix.

Section 1 (Phase 1, previous housing situation)

The first section of the Phase 1 survey is where the occupant is asked to describe their current living situation, including the type of property they are living in, the heating systems present, and their behaviour – specifically with regards to perceived control of the heating system and the thermal environment, and their use of windows and doors for ventilation purposes. This section also covers a brief assessment of thermal comfort. The design of questions was influenced by methods from Francis' *et al.* survey design manual, and by recent similar studies such as that by Gill *et al.* (Francis et al., 2004; Gill et al., 2010).

Section 1 (Phase 2, new housing situation)

The first section of the Phase 2 surveys concerns the resident's experience over the time they've been in the apartments so far. Since the properties of the flats are known, these questions instead focussed on the behaviour and experiences so far, including: thermal comfort, perceived control of systems and thermal environment, and use of windows and doors for ventilation.

Section 2 (Phases 1 & 2)

The second section deals with environmental attitude, norms and control using scales developed by Kurz and Linden at Belfast University (Kurz, Linden, & Sheehy, 2007). The attitude score is built up based on answers to a number of questions using 5-point Likert-type scales (e.g. 1 = Strongly Agree, 2 = Somewhat Agree, 3 = Neither Agree or Disagree, 4 = Somewhat Disagree, 5 = Strongly Disagree).

Scales of 5-points were chosen for ease of understanding of the survey occupants, and based on influential research by Miller and Preston & Colman which advise on the detrimental effect of using too many points on a Likert-type scale (Miller, 1994; Preston & Colman, 2000) and the relatively good performance of scales in the 7 and 5 point ranges.

Also included in this section are a few questions to assess perceptions behaviours in the context of social norms. The Phase 2 survey is identical to the Phase 1 survey in this case, giving a chance to contrast scores after a period of living in the apartments.

Along with Perceived Control scores, these Attitude and Subjective Norm scores can be used to predict Behavioural Intention as per the Theory of Planned Behaviour (see Figure 1.10), in a similar fashion to Gill *et al.* (Gill et al., 2010), shown in (2.3) below.

It is noted some questions require the scales to be flipped, i.e. an answer in the negative should be scored as a positive and vice versa.

$$\begin{aligned}\text{Total behaviour score}\\ &= \text{attitude score}\\ &+ \text{subjective norm score}\\ &+ \text{control score}\end{aligned} \tag{2.3}$$

Section 3 (Phases 1 & 2)

The third section is a short (1-page) section focussed on demographic information, and to capture any changes in the household as a whole between Phases 1 and 2 (i.e. number of occupants, occupancy schedule, income etc.).

Part 1 of this work discusses the implementation of the surveys and includes analysis of the resulting data.

Methodology Summary

Since a major aspect of the design-performance energy gap discussed in Part 1 is attributed to occupant behaviour, a methodology is developed to further understand its impact on energy use.

In Section 2.1 of the methodology a third-party tool for generating stochastic electric use profiles is modified to output annual profiles for occupancy, lighting and appliance usage (Richardson, Thomson, et al., 2010). In addition, door-opening profiles are created based on occupancy changes, and heating thermostatic set-points are generated based on measured data in Passivhaus buildings using data from the CEPHEUS Project (Schnieders, 2003) for calibration.

In Section 2.3 a number of options are considered for collection of qualitative data about occupant attitude and behaviour, and a survey with open-ended interview questions is decided upon, using the theory of planned behaviour to underpin development of questions. A study is detailed in two distinct phases: Phase 1 of the survey is carried out before the occupants move into their new Passivhaus housing, and Phase 2 is to be carried out at least one year after living in the new homes. The full surveys are included in the Appendix to this thesis for reference.

Part 3 Behavioural Simulation

In this part of the thesis, the methodology described in Section 2.1 is employed to generate both semi-static (PHPP software) and dynamic (IES VE) thermal models of Passivhaus dwellings, with occupancy levels, appliance and lighting usage which is representative of UK households, and setpoint temperatures in a range similar to those found in European Passivhaus buildings. Semi-static software was shown to estimate the average heating energy use quite well, however the range of energy use was not comparable. A dynamic simulation was shown to emulate a similar range of behaviours as those measured in real Passivhaus dwellings.

A regression model is constructed to understand the impact of certain parameters on the heating energy use of a household. Parameters included in the model are heating setpoint, average appliance energy use, average lighting energy use, airflow gains, and average occupancy level. This multi-parameter equation is shown to represent the impact of certain behaviours well in this circumstance. The idea of a five-term regression equation to represent a range of occupant behaviour in a household is enticing, both for academics looking for fast calculations and for designers who are looking to anticipate expected ranges of energy use. Limitations of this approach are also discussed.

3.1 Synthesising Occupant Behaviour Profiles

In this section, occupancy, appliance-use, and door-opening profiles are generated using a modified form of the third-party tool introduced in the preceding sections (Richardson, Thomson, et al., 2010). This tool is informed by a survey of 20,000 weekly UK household journals, which detail time use (activity at a certain time) at a ten-minute resolution by 11,600 individuals (Ipsos-RSL, 2000). These profiles are used in the thermal model of a Passivhaus to represent unique households, which, by nature of the method used to derive the profiles, represent statistically likely behaviour. The results of this generation are validated using comparisons to measured data from Passivhaus projects around central Europe (Schnieders & Hermelink, 2006) and data gathered in the UK from two separate studies (Gill et al., 2011; Richardson, Thomson, et al., 2010).

Representing behavioural variation

Mahdavi *et al.* has very recently published excellent work in the field of representing occupant behaviour, in particular in the study of predictive modelling of occupancy using probabilistic and non-probabilistic methods (Mahdavi & Tahmasebi, 2015).

It is clear that the field of demand-side load-modelling could be a useful resource when beginning to generate synthetic household profiles. Of interest to the load modeller is electrical load, which is dependent on occupant activity, and of interest to the designer is the thermal performance under the same loads. This crossover led to the investigation of a number of DSM synthesis techniques, seen in Section 2.1. It was the Markov Chain techniques such as that employed by Richardson *et al.* in the UK, and Widen ***et al.*** in Sweden which used statistically relevant and robust methods for synthesis of occupancy data (Richardson et al., 2008; Widén et al., 2009).

As previously introduced, the Markov Chain technique is an established stochastic method for generating data for a system with a discrete number of possible states (Gilks et al., 1995). A first-order Markov-chain means that the change of state within the system is dependent only on the current state, not on any preceding states.

The representation of occupancy in the model provides the primary method for creating synthetic electricity demand data with appropriate aggregate daily profiles. This technique for generating occupancy profiles uses a ten-minute grid of the current states together with the probability of an occupancy state change at the boundary to calculate whether a change of state occurs in the next period (Richardson et al., 2008).

To create the high-resolution appliance-use profiles Richardson et al. use the TUS data to define 'activity profiles', where a particular listed activity has associated appliances that have a certain chance of a switch-on event occurring. Combined with details of the mean power use and cycle lengths for each appliance (from various sources, see (Richardson, Thompson, et al., 2010)), load profiles are stochastically generated. For example, the activity labelled 'Cooking' may involve a combination of the following appliances cycling one or more times: electric hob, electric oven, and microwave.

The base occupancy profiles are also used to represent internal heat gain from occupants in the thermal model, and furthermore, they form the basis for the 'door-opening' event profiles.

These profiles are useful since they have been shown to display similar statistical characteristics to measured UK appliance-use and occupancy patterns and hence they can be used to represent a range of likely UK behaviours.

Profile generation

100 appliance-use and occupancy profiles were generated for weekdays and weekends, each month of the year, making a total of 2,400 runs of the Richardson tool and 9,600 unique ten-minute resolution profiles representing appliance use, lighting, occupancy, and door openings. The number of simulations was picked to achieve a balance between statistical significance and manual work, since each simulation was not entirely automated. This was achieved by writing software in visual basic that extracted the data from the Markov model and converted this into a text file that could be read by the thermal model in place of the normal profile generation interface. Example outputs are shown in Figure 3.1.

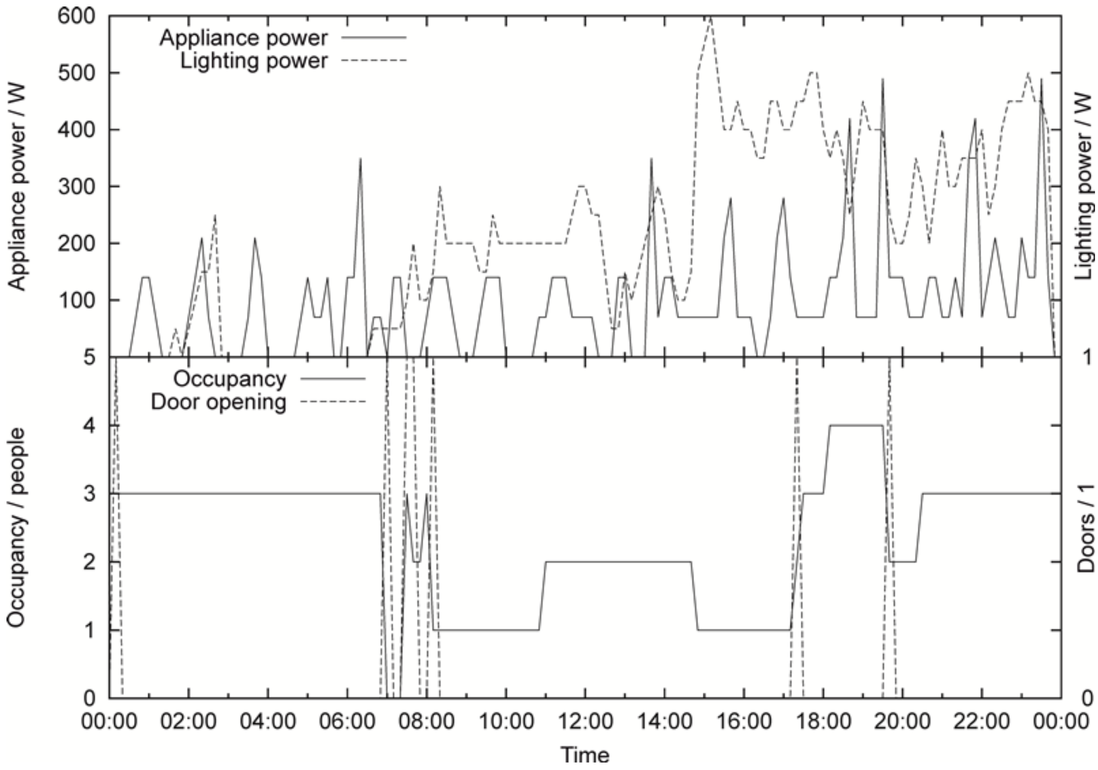

FIGURE 3.1 - EXAMPLES OF THE STOCHASTICALLY GENERATED LIGHTING, APPLIANCE, DOOR-OPENING, AND OCCUPANCY PROFILES FOR A 4-PERSON HOUSEHOLD.

Because the appliance-use profile is generated from the occupancy profile, which has a dependency on the month, there are essentially 100 unique household profiles for each month of the year and these are not linked to those of the previous month. This is unlikely to represent reality as, for example, occupancy levels are likely to be relatively static until the dwelling changes ownership. Hence a method is needed that ensures similar appliance-use and occupancy profiles are maintained at the boundary of each month. To achieve this household profiles were matched via a ranking variable f as shown in (3.1). Where E_{max} is the peak electricity load, $\bar{E}$ is the mean electricity load, and $\bar{O}$ is the mean occupancy.

$$f = \frac{E_{max}}{\bar{E}} + \bar{O} \quad \textbf{(3.1)}$$

f behaves such that steady appliance-use profiles score lower than more erratic profiles, thereby helping to group those profiles with a lesser variance to others with similar magnitudes of variance. For example, a household of professional 'sharers' is likely to have an erratic electric usage and relatively low occupancy compared to an elderly couple who spend more of the day at home. This ranking method will sort similar monthly behaviour profiles into full years, i.e. in our example the elderly-January would be paired to an elderly-February, and so on.

To form annual profiles, monthly profiles were ranked by f and grouped by position in the resulting ranking table. Appliance-use profiles were then normalised with respect to the highest electric load across the year for each household. The resolution of the power profiles were decreased by averaging over every ten-minute period. This effectively maintains the average power of the electric profiles and improves computational speed.

Heat gains per active occupant were set to 75 W sensible heat and 55 W latent heat, as per the CIBSE recommendations for gains associated with standing, light work, and walking (Chartered Institution of Building Services Engineers, 2006).

The occupancy profiles generated by Richardson *et al.* are designed to represent active occupants only. This means that the software does not discern between absent and sleeping occupants, however sleeping occupants still contribute to sensible and latent heat gains. To represent night-time occupancy gains (when the occupants are likely to be asleep) a simple heuristic was used such that occupancy between 22:00 and 07:00 (which would indicate either sleeping or absent occupants) does not fall below half-occupancy, activity above this is recorded while activity below this level is discounted.

The reporting interval or timestep-resolution of an energy model is a balance between gaining a clear picture of changes in the model, and having unwieldy runtimes and result datasets. The simulation engine can handle calculations down to 1-min interval, and reporting at a 6-min interval, however since the weather file is an hourly interval, and the stochastic data will be generated at a 10-minute interval, a sub-10 minute interval would not offer further insight.

To account for uncontrolled ventilation from occupants leaving and entering the building, it is proposed that every time the occupancy profile changed the door would open for 15 s. Due to the limitation of the 1-min. minimum calculation timestep in IES, every door opening of one minute represents four changes in the occupancy profile preceding the event.

The windows were set to open when both the temperature rose above 27 $°C$ (subject to proportional band of ±1 $°C$) and the CO_2 concentration rose above 480 ppm (ambient CO_2 level is 360 ppm in IES 2012, which is lower than average CO_2 concentrations seen today (NOAA-ESRL, 2014)). The minimum CO_2 criterion ensures that there are occupants present in the house to open windows when the temperature reaches this level. 480 ppm is a relatively low indoor CO_2 concentration, normally reached within an hour of a person being present in the home, with mechanical ventilation active. As only Passivhaus buildings were considered, winter ventilation is provided by a mechanised system.

In this work, the temperature is assumed to be controlled to a specific temperature by the heating system. The set-point is randomly assigned from a normal distribution of preferred temperatures with a mean and standard deviation identical to that measured in Passivhaus units in Central Europe (Schnieders, 2003). The original measured data shows normal characteristics, with a skewness of -1.21 and a kurtosis of 3.06 – indicating a Gaussian distribution. The mean normalised temperature was 21.56 $°C$ the standard deviation (σ) was 1.81 $°C$. Figure 3.2 shows the resulting distributions. Randomised temperatures were generated exhibiting similar statistics. It is worth noting that this method can produce extreme set-points, for instance 27 $°C$ or 16 $°C$, 3σ from the mean ($P < 0.1\%$). This is known to conflict with the window opening profile (opens at 27(±1) $°C$ & > 480 ppm CO_2). However such outliers were kept since such set-points, whilst extremely rare, are not unknown – anecdotally see Building Magazine article by Thomas Lane (Lane, 2010).

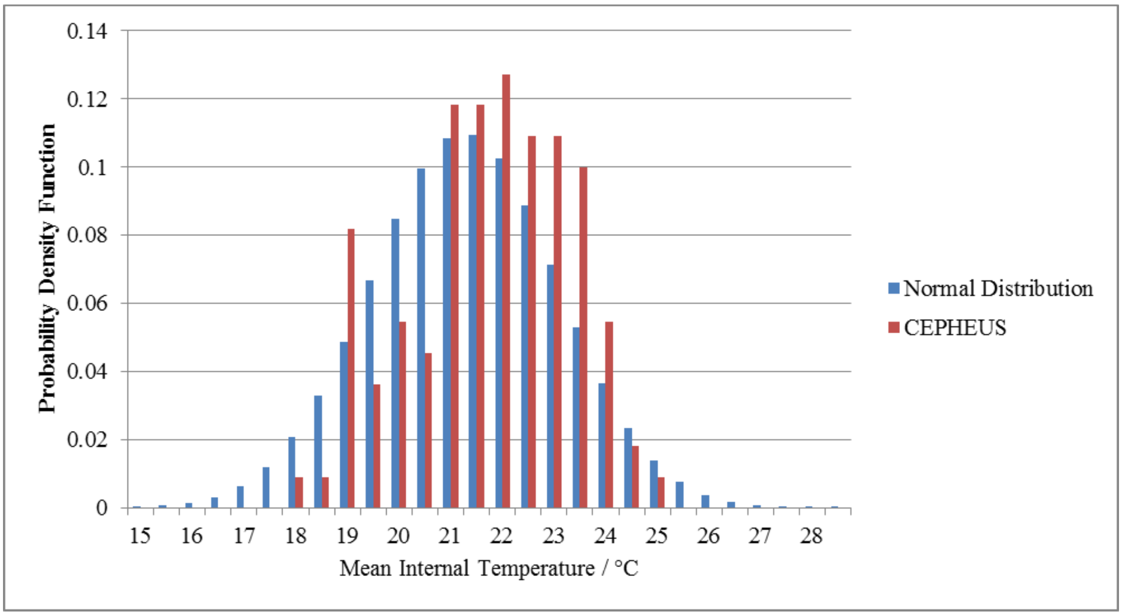

FIGURE 3.2 - COMPARISON OF THE MEASURED TEMPERATURE DISTRIBUTION THROUGHOUT THE CEPHEUS PROJECT AND THE NORMALLY-DISTRIBUTED MODEL USED IN THIS STUDY.

3.2 Simulation

Integrated Environmental Solutions 'Virtual Environment' (IES VE) thermal modelling software was used to model the Passivhaus buildings, a popular tool for commercial uses and also academic. IES was chosen as the software with which to simulate occupant behaviour due to the ease with which one can build a model of a building, and generate input profiles for gains patterns.

This package can resolve events at one-minute intervals, and includes a dynamic representation of airflows ('Macroflo'), used to describe internal and external airflows, such as the door and window openings discussed previously.

The building itself is a three-storey family home with a treated floor area of 156 m^2. A single-pitched roof extends from the lower north side to the higher south face of the building; the pitch is such that the terrace has two stories on the northern half of the unit and three stories on the southern half. The glazed area is 25% of the treated floor area. Table 2 presents the thermal transmittance and area of various building elements. The construction and system details were modelled as closely as possible to the details available for the Kranichstein terraces given in the Passive House Institute's PHPP 2007. The geometry of the dwelling is shown in Figure 3.3, Figure 3.4 and Figure 3.5 below.

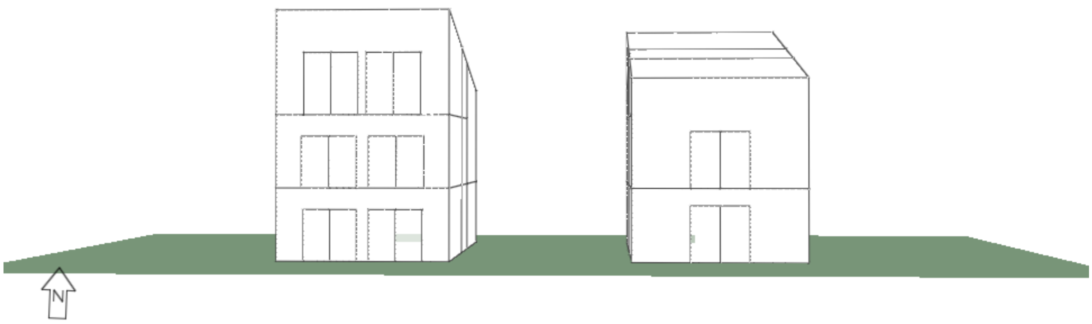

FIGURE 3.3 - A RENDERING OF THE IES VE MODEL OF THE KRANICHSTEIN PASSIVHAUS TERRACES TO INDICATE GLAZING LEVELS ON FRONT (SOUTH) AND REAR (NORTH) ELEVATIONS, AND MODEL GEOMETRY. NOTE – TERRACE HAS BEEN ROTATED 180 DEGREES PURELY FOR VISIBILITY OF BOTH ELEVATIONS. GREY LINES INDICATE GLAZING GEOMETRY AND SURFACE JOINS (E.G. LINES VISIBLE ON ROOF CORRESPOND TO INTERNAL WALLS UNDER THE ROOF).

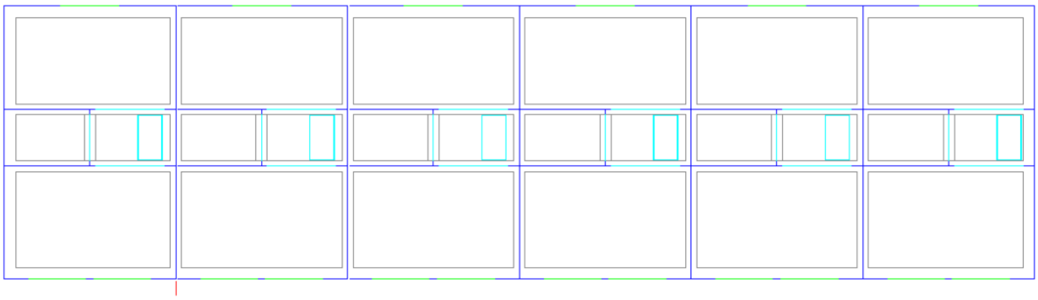

FIGURE 3.4 – PLAN VIEW OF THE PASSIVHAUS TERRACES MODELLED IN ONE 'BATCH'. APACHESIM WAS LIMITED TO MODELLING SIX DWELLINGS AT A TIME DUE TO LIMITATIONS WITHIN THE VE AND THE HIGH-RESOLUTION PROFILES IN EACH MODEL. TWO OF EACH SIX ARE INCLUDED IN THE THERMAL SIMULATION BUT IGNORED IN THE FINAL ANALYSIS AS END-OF-TERRACES. DARK BLUE LINES INDICATE INTERIOR AND EXTERIOR MODEL WALLS, LIGHT BLUE REPRESENT 'HOLES' (I.E. DOORWAYS VOIDS), AND GREEN LINES REPRESENT GLAZING AND DOORS. FAINT GREY LINES REPRESENT THE VOLUME BETWEEN SURFACES (INNER VOLUME REPRESENTATION).

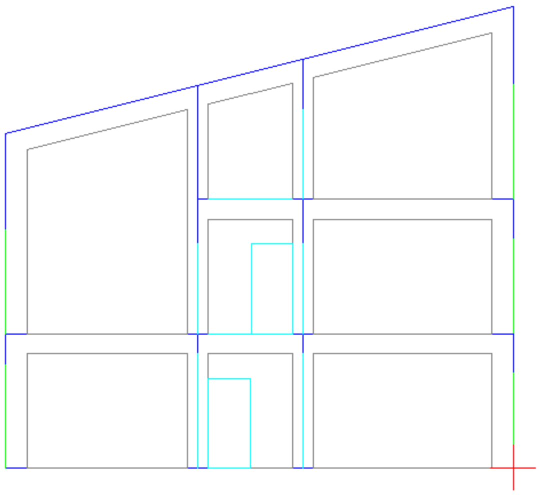

FIGURE 3.5 – LEFT ELEVATION OF THE PASSIVHAUS TERRACES MODELLED IN IES. DARK BLUE LINES INDICATE INTERIOR AND EXTERIOR MODEL WALLS, LIGHT BLUE REPRESENT 'HOLES' (I.E. DOORWAYS VOIDS), AND GREEN LINES REPRESENT GLAZING AND DOORS. FAINT GREY LINES REPRESENT THE VOLUME BETWEEN SURFACES (INNER VOLUME REPRESENTATION).

The overall thermal transmittance of the modelled building envelope was 0.19 $Wm^{-2}K^{-1}$. A static shading factor of 0.38 across all windows is included, and solar shading from overhangs and the depth of glazing is applied. The airflow was set to mechanical ventilation for 7 months of the year, reverting to natural ventilation for the remainder. The winter ventilation rate was 0.3 ach^{-1} in all spaces at all times of day, as in the PHPP Kranichstein terraces. For the heated period, the thermostat was set to a set-point dependent on household preference as previously described. The efficiency of the heat-recovery system was set to 82%. No cooling system was used, although as noted above, there was a proportional window opening event if the temperature of the occupied house reached 27 (±1) $°C$. Infiltration was specified at 0.047 ach^{-1} as per the PHPP model.

Automation of the Simulation Process

To implement the proposed method, automation of profile synthesis and input was necessary to avoid an impractical amount of manual data entry through the IES ApachePRO module. Firstly a method was devised to automate the synthesis of occupancy profiles using VBA macros embedded into the Richardson tool. Then the synthesised profiles needed to be stored in the appropriate IES files so they would be included in the simulations. Once the profiles were complete IES could be run in 'batch' mode to remove the need for user interaction between runs. The majority of the manual work was in extracting the results from IES, for which there is currently no shortcut to 'batch' this operation[9].

Richardson Tool to ApachePro files:

A modified form of the Richardson tool (see Figure 3.6) is informed by user inputs which dictate the number of runs at each level of occupancy, whether weekends are considered, if appliances are randomised, and some other important parameters (see Figure 3.7). The macro then reads this information and loops runs of the tool as necessary. The occupancy, appliance use and lighting use data is exported after each run, and stored in a separate sheet. From this sheet, it is formatted into profiles appropriate for use in the IES ***.pdb*** (day profiles) files. The ranking coefficient (3.1) is then calculated for each profile, and they are sorted into appropriate annual groups. Now the weekly and annual profiles are constructed to be stored in a separate IES file, the ***.pro*** (week/year profiles) file.

All daily profiles are 'modulating' which means division by a constant larger than the maximum value to create a fractional value. Using this maximum value in the IES model means that any of the profiles can be used in the same model and not cause computation issues where a modulating value is >1. Finally the VBA macro, on approval, will modify the profiles in the specified IES folder to include these synthetic profiles.

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[9] As of December 2014, IES VE 2014 Feature Pack 2 is able to batch output, allowing almost full automation of the described process.

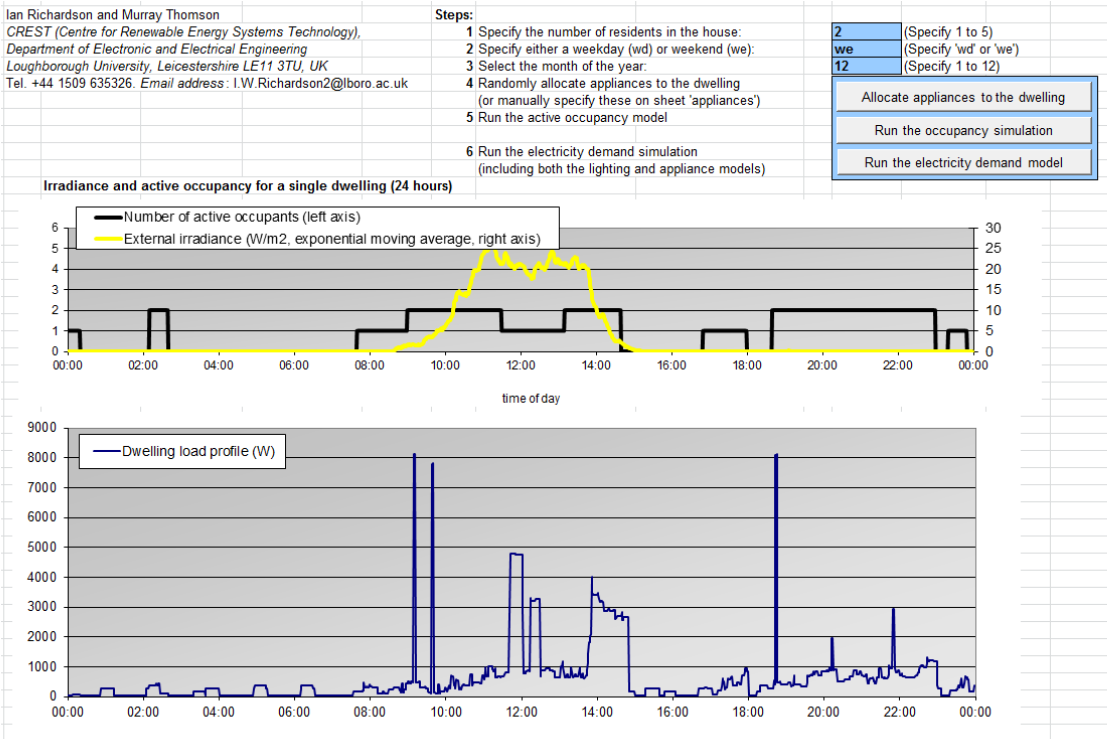

FIGURE 3.6 - SCREENSHOT OF THE MAIN WINDOW FROM WHICH THE RICHARDSON TOOL IS RUN.

This process is automated through the use of macros, and takes approximately $4s$ per generation, therefore the 2,400 runs take roughly $2h\ 40m$ via this procedure.

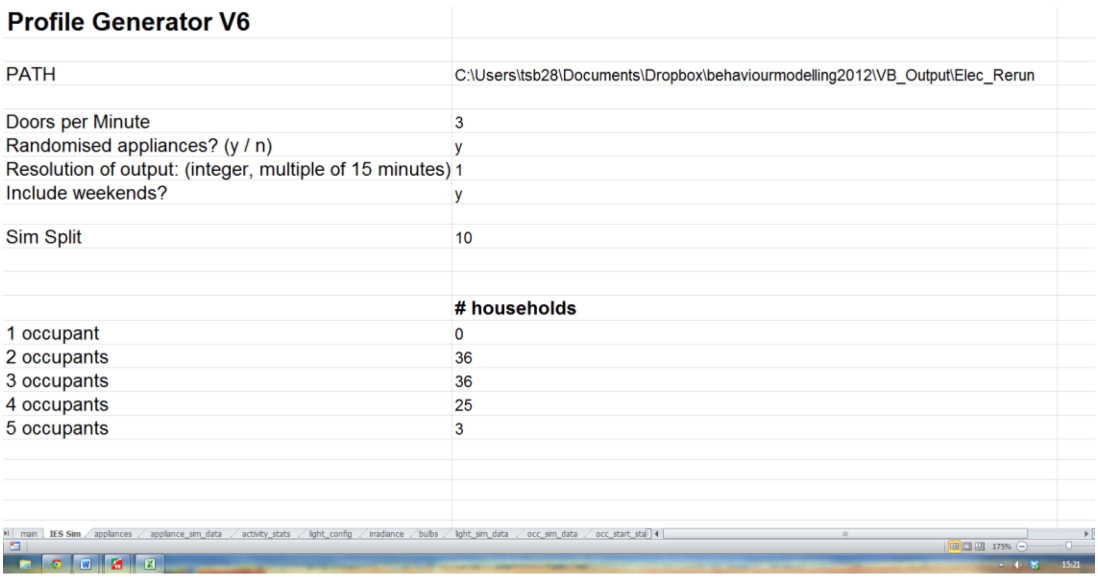

FIGURE 3.7 - ADDITIONAL USER INPUTS FOR THE MODIFIED RICHARDSON TOOL, FOR THE SYNTHESIS OF THERMAL PROFILES.

Running an IES Batch

The final part of the operation is the least-automated and most demanding on the user-side – once the IES geometry and ApacheSim profiles are correctly established, the model can be copied the appropriate number of times, and added to a batch queue. The final stage of the previously described macro populates the appropriate folders with the correct profiles, so the 'batch simulation' function in IES VE can be used to begin a number of predefined simulations.

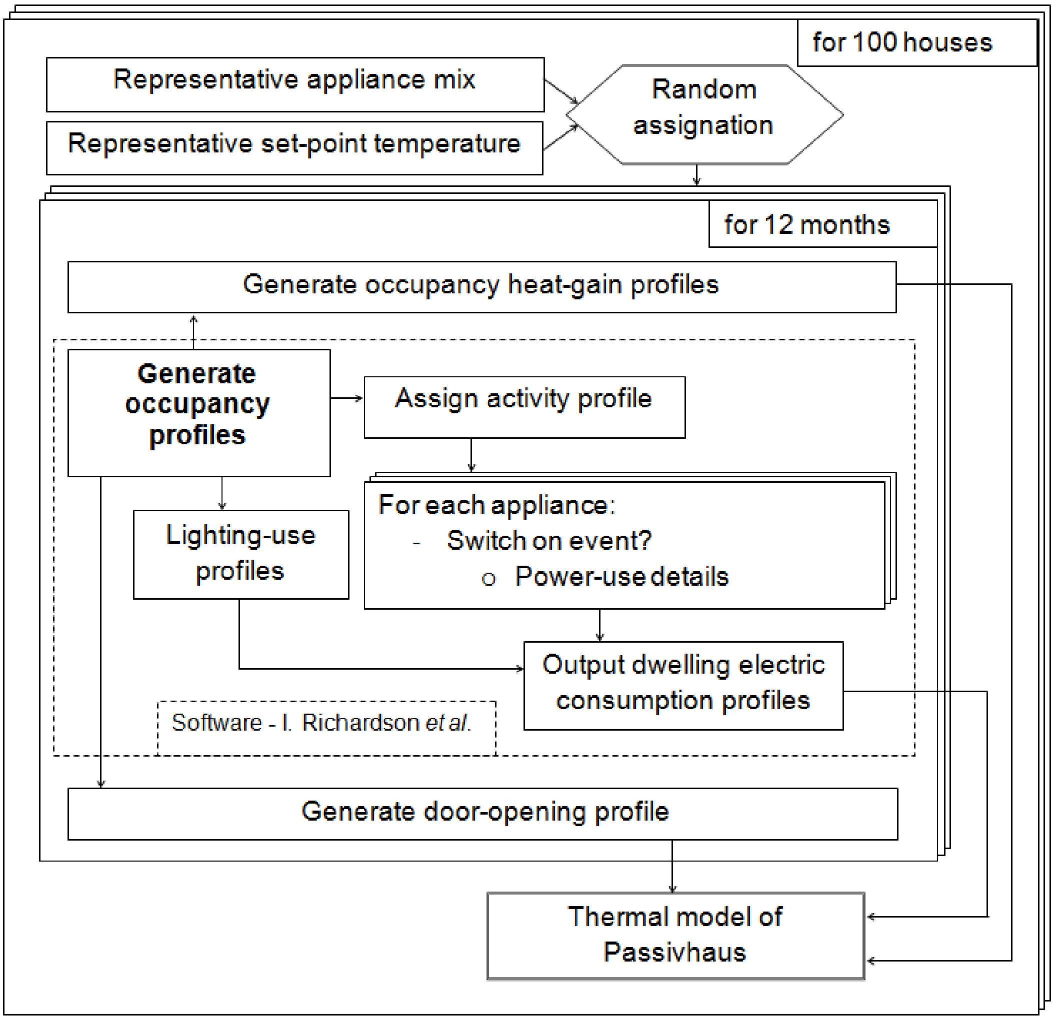

FIGURE 3.8 - SIMULATION INPUTS AND OUTPUTS EXPLAINED IN NESTED FORMAT. DOTTED LINES HIGHLIGHT THE MODIFIED CONTRIBUTION OF THE SOFTWARE BY RICHARDSON ET AL. [10]

Figure 3.8 shows an overview of the various inputs to the thermal model, and summarises the origin of each variable. The nested loop is run for twelve months of the year, whereas the outer loop runs for each of the 100 houses, after the annual profiles have been assembled via (2.1), as described previously.

Dynamic simulation output

In verifying the model outputs, firstly it is prudent and recommended practice to check the aggregate outputs, or headline figures, to determine if there are any

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[10] Figure reprinted from (Blight & Coley, 2013) with permission from Copyright holder.

unexpected results – a sanity check on the summed totals is fast and simple to do. Then it is worth looking at the variable behaviour at a high resolution, to check that the gains and temperatures calculated are following anticipated patterns, e.g. using the method described in this section, one expects some airflow gain as doors open, which occurs for one minute every four changes in occupancy (this is confirmed by Figure 3.9 below).

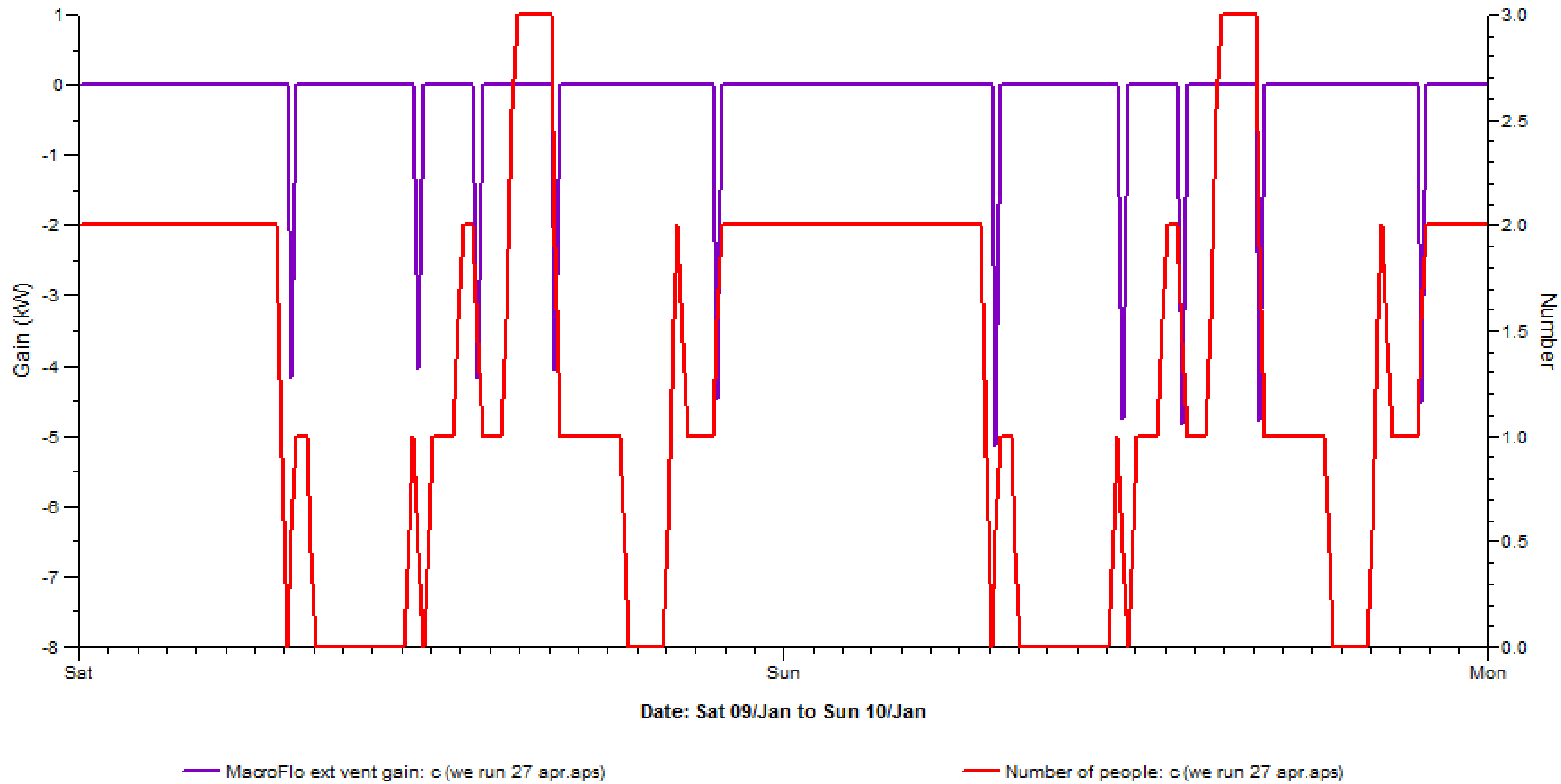

FIGURE 3.9 – OCCUPANCY CHANGES IN ONE HOUSEHOLD PLOTTED ALONGSIDE EXTERNAL VENTILATION GAIN FOR TWO COLD DAYS IN THE YEAR.

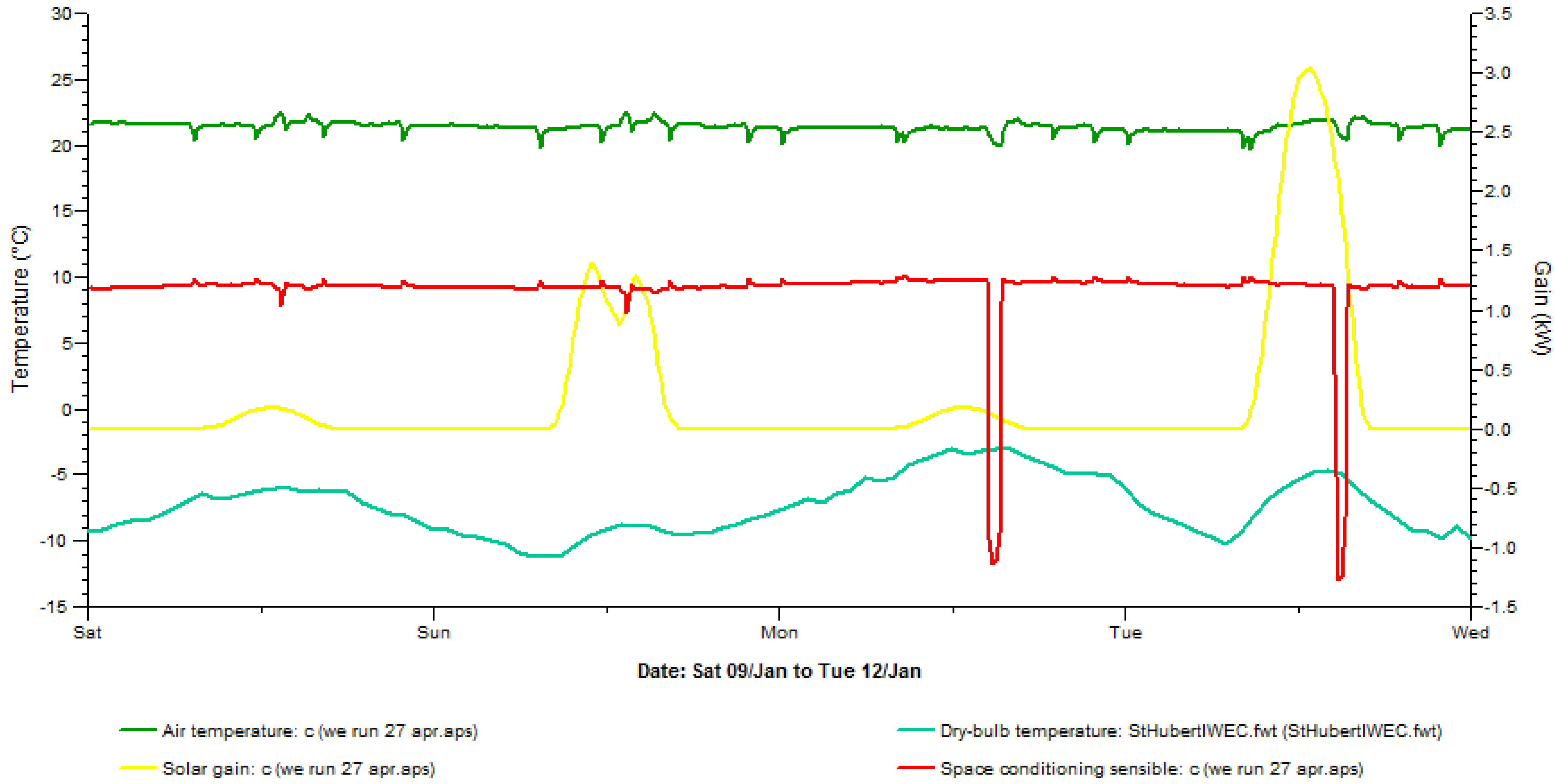

FIGURE 3.10 – INTERNAL AND EXTERNAL AIR TEMPERATURE (℃), SENSIBLE SPACE HEAT AND SOLAR GAINS (kW) FOR ONE HOUSEHOLD PLOTTED AGAINST TIME, OVER FOUR COLD DAYS IN JANUARY.

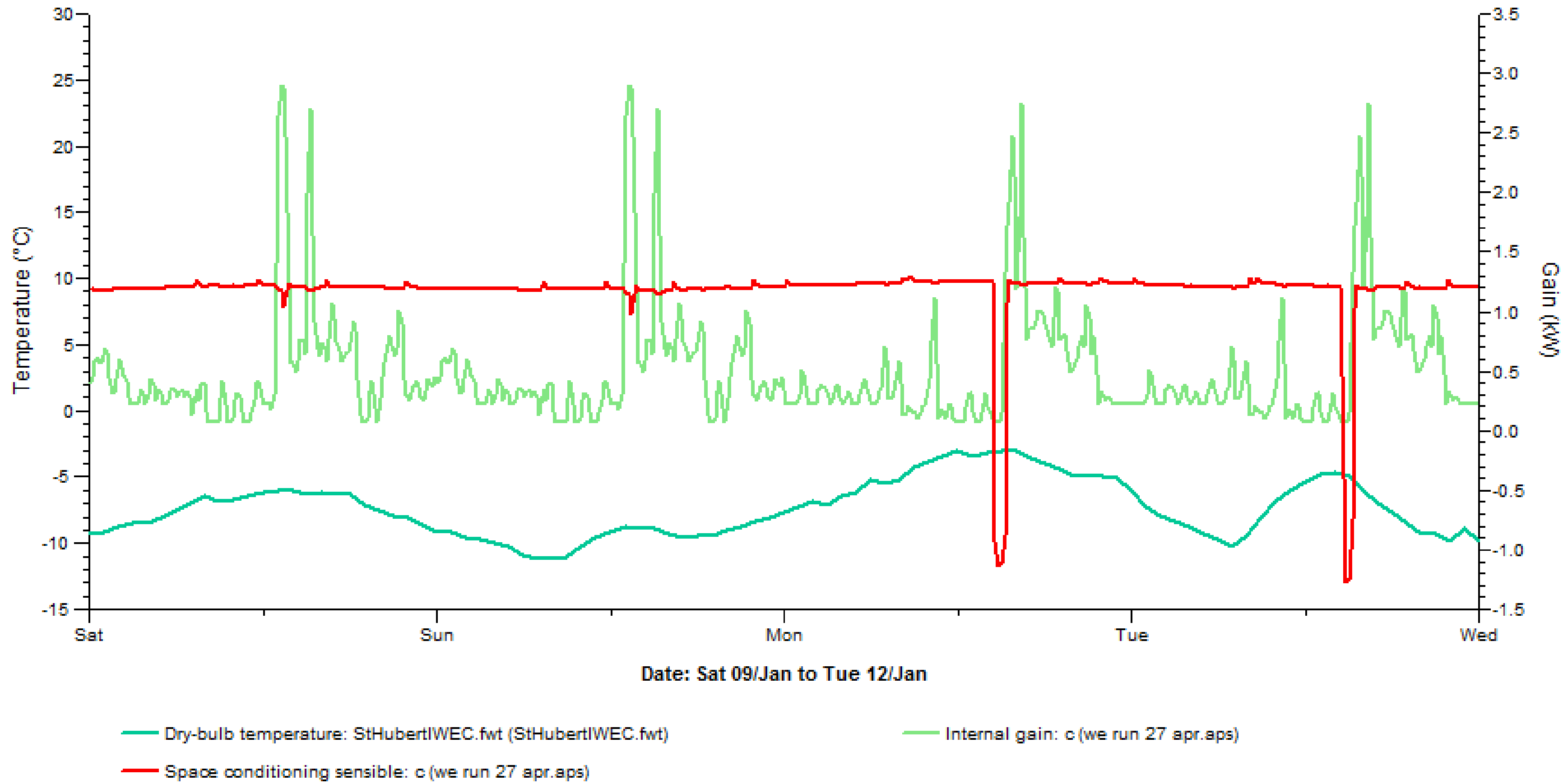

FIGURE 3.11 – EXTERNAL DRY-BULB TEMPERATURE (℃), INTERNAL GAINS AND SENSIBLE SPACE CONDITIONING (kW) IN A HOUSEHOLD PLOTTED AGAINST TIME ACROSS FOUR COLD DAYS.

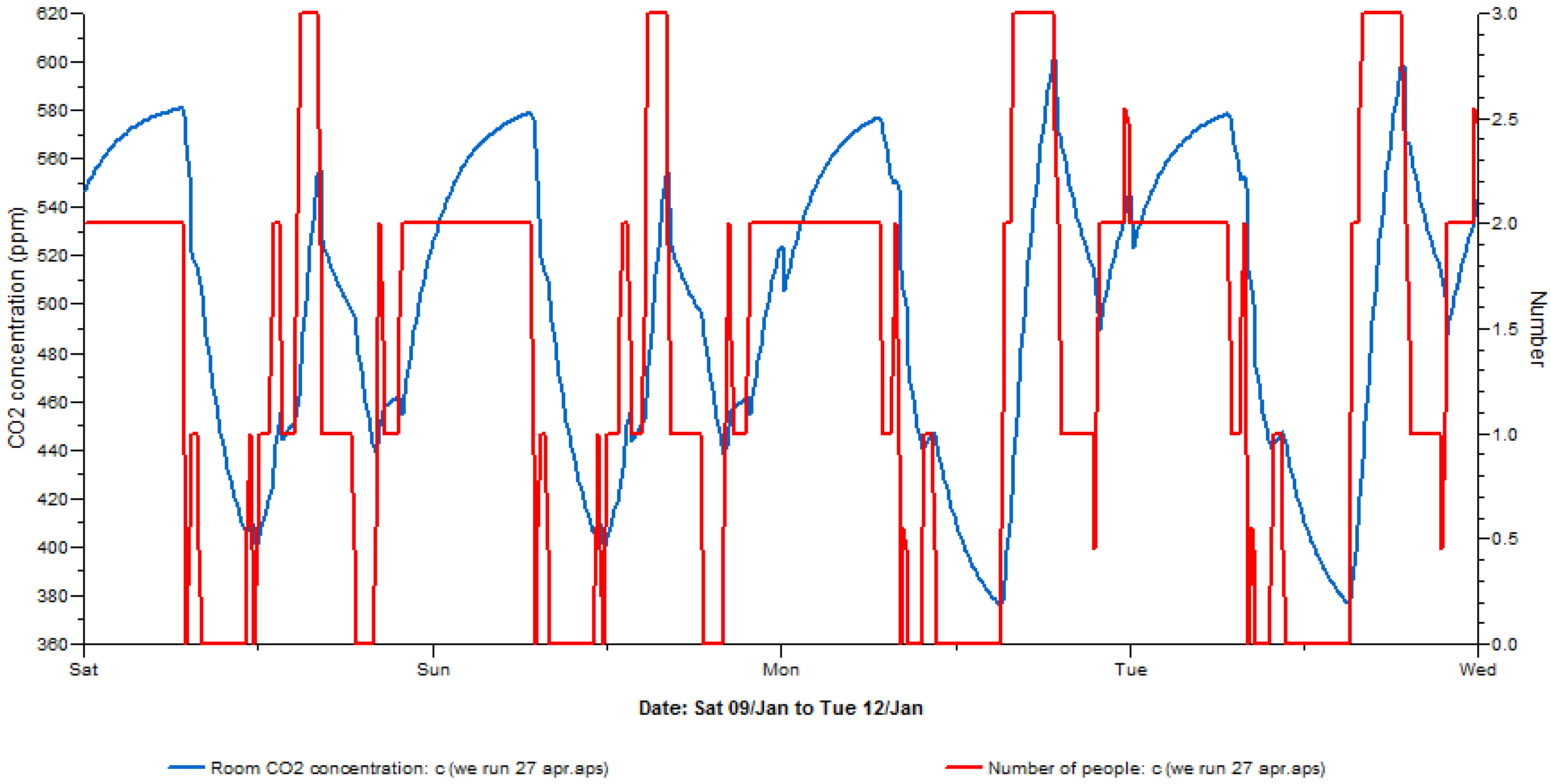

FIGURE 3.12 – AVERAGE CO2 CONCENTRATION (ppm) AND OCCUPANCY LEVEL PLOTTED AGAINST TIME OVER FOUR DAYS.

PHPP simulation output

In addition to the modelling using IES VE, a modified version of the Passivhaus Planning Package (PHPP 2007 Edition) was developed to run a calculation of the same range of occupant behaviour as is described in Section 3.1.

Setup of the model is straight-forward, since PHPP 2007 ships with example files for the Darmstadt Passivhaus buildings, so the dynamic models were based upon values found in the PHPP example sheets. The Monthly Calculation Method was used. For details on the calculation methods behind PHPP software, please refer to the PHPP Manual, available with purchase of the software.

A simple macro cycled through a number of simulation settings and record the resulting space heating energy. The number of occupants, internal heat gain, and internal temperature set-point cells were cycled through the outputs of the application described previously – appliance use, lighting, and occupancy were summed as internal heat gain for this purpose.

It should be noted that this modification does impact the validity of the PHPP software. In altering the internal gains, the software is no longer operating within the same bounds as the original PHPP, and would not be accepted for Passivhaus certification purposes.

The results of the simulation can be seen in Figure 3.13 plotted against measured results from the CEPHEUS project (Schnieders, 2003).

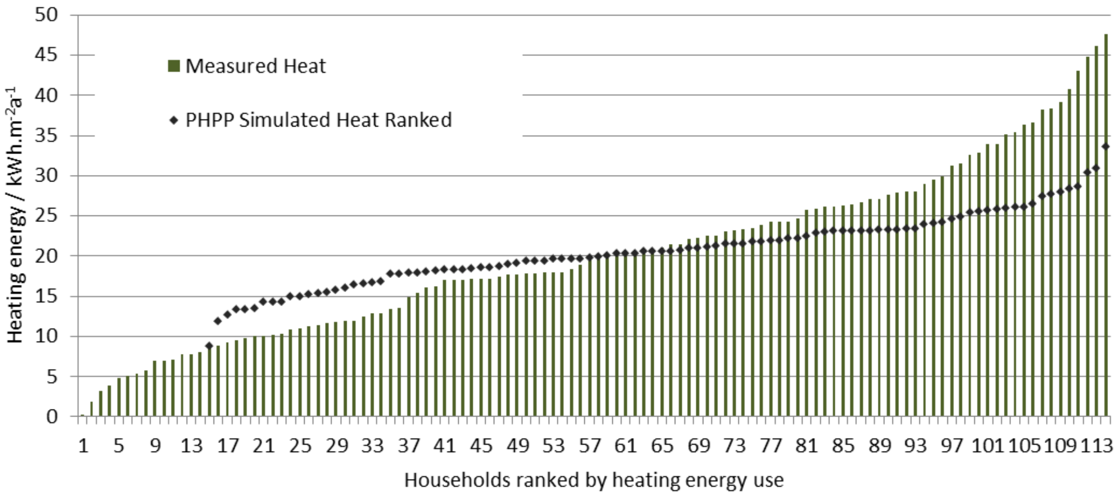

FIGURE 3.13 – PHPP BEHAVIOURAL SIMULATION (POINTS) PLOTTED AGAINST THE HEATING ENERGY DATA MEASURED IN THE CEPHEUS PROJECT (BARS).

The results suggest that PHPP is able to represent some extent of the range of behaviour, however not nearly the full range. The impact of building form and design will also have some baring on the output, though these variables are more constrained with Passivhaus certification. The results appear somewhat stepped, which is due to the setpoint temperature being rounded to the nearest 0.5°C, and a high dependency on temperature.

3.3 Building Model Verification

The validity of this BU modelling approach was verified by a comparison of the predicted results with measured energy data to data from the 'Cost Efficient Passive Houses as a European Standard' (CEPHEUS) project, an assembly of measured data from 113 European Passivhaus certified new-build dwellings. Over the project heating energy and appliance electrical energy usage was measured (along with DHW and internal conditions), each of which is compared to the output of the simulation.

Using a study of appliance usage throughout Europe (ODYSSEE, 2009), Figure 3.14 shows the different trends seen between various countries, which ranges from 1000 $kWh.a^{-1}$ (Estonia, Romania) to over 3500 $kWh.a^{-1}$ (Sweden, Finland), with the EU average equal to 2599 $kWh.a^{-1}$. Such differences are due to a variety of cultural, physical and economic influencing factors, with the culminating components being number of appliances owned, efficiency of the appliance, and efficiency of usage. The labelled columns were used to form a weighted average representative of the CEPHEUS project giving a result of 2670 $kWh.a^{-1}$, which is 25.8% lower than the average for the North-East Midlands.

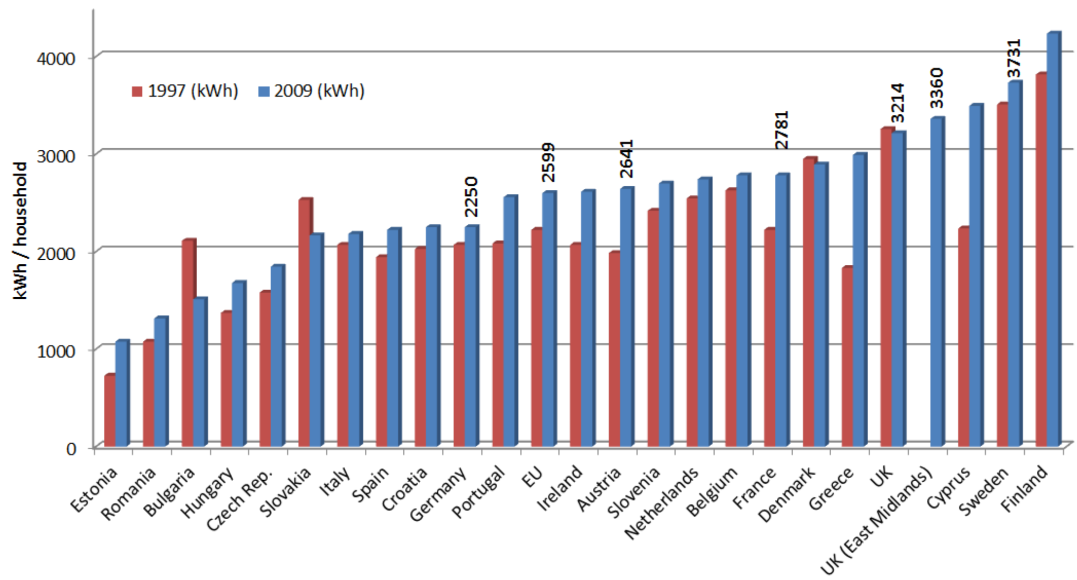

FIGURE 3.14 – ANNUAL HOUSEHOLD APPLIANCE & LIGHTING ELECTRICITY USE IN EUROPEAN COUNTRIES (ODYSSEE, 2009), WITH AN ADDED DATA POINT FOR THE SITE IN THE EAST MIDLANDS FOR WHICH THE RICHARDSON TOOL WAS CALIBRATED (RICHARDSON, THOMSON, ET AL., 2010), ASSUMING A MEAN HOUSEHOLD SIZE OF 2.3.

Figure 3.15 shows the annual heating energy and electric energy results from the simulated terraces and the equivalent measured data from the CEPHEUS project in $kWh.m^{-2}a^{-1}$. The main chart displays a side-by-side heating energy comparison of the individual measurements vs. the simulation, while the sub-chart in Figure 3.15 shows a summary of the heating energy and the electricity used from appliances, lighting and auxiliary systems.

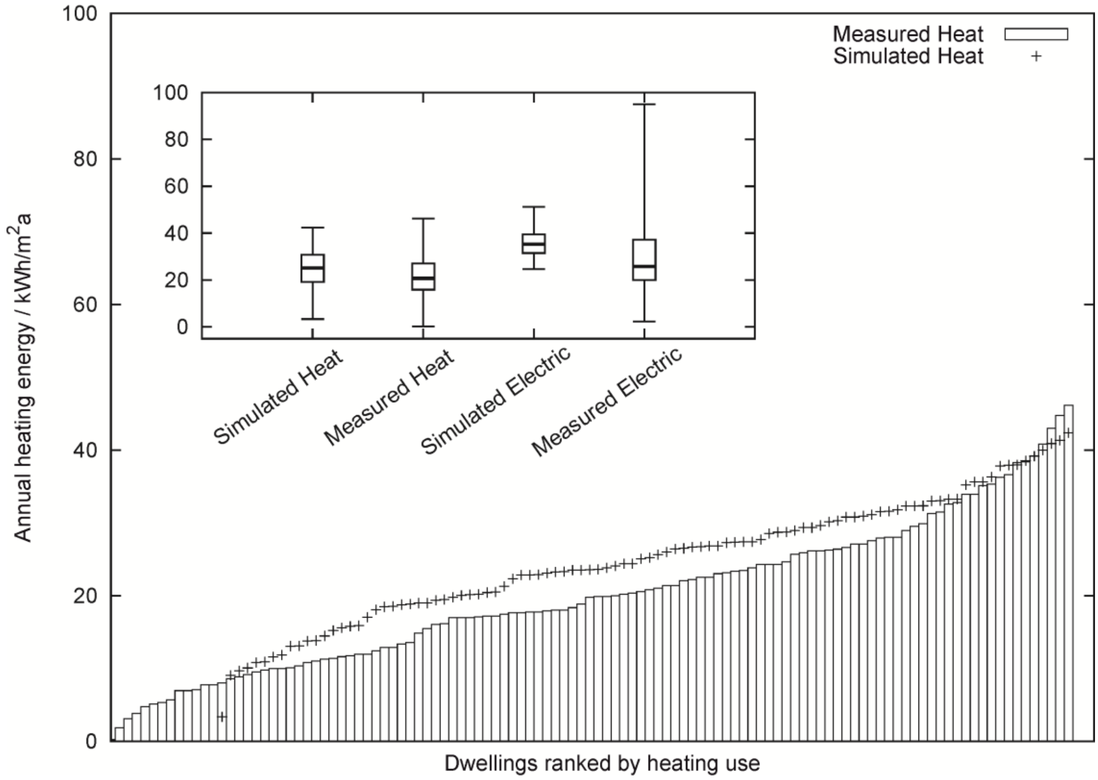

FIGURE 3.15 - MAIN: THE RANGE OF THE RESULTS FOR HEATING ENERGY REQUIRED OCTOBER THROUGH APRIL. SUB-CHART: BOXPLOTS MARK THE MAXIMUM, MINIMUM, UPPER QUARTILE (UQ), LOWER QUARTILE (LQ), AND MEDIAN FOR THE HEATING ENERGY AND TOTAL ELECTRICITY USED IN THE MEASURED AND SIMULATED RESULTS.[11]

The measured data has a greater range, since the model has a limited representation of extreme usage, e.g. no holiday periods are represented, and no occupancy is considered below 2 or above 5. It is apparent that the majority of the measured distribution is equivalent to or lower than the IES VE model, particularly considering the LQ and median values.

The median values of both heating datasets in are above the Passivhaus requirement of 15 $kWh.m^{-2}a^{-1}$. This is due in part to higher set-point temperatures beyond the 20°C assumed in the 15 $kWh.m^{-2}a^{-1}$ target, and in the measured results possibly also due to issues associated with the measurements being made in the first year; notably the 'drying-out' of constructions, and the occupants acclimatising to the new systems – which may increase consumption. The average simulated heat output is

[11] Figure reprinted from (Blight & Coley, 2013) with permission from Copyright holder.

21% higher than the measured data, but represents the range of heating reasonably well.

Electricity use, or the sum of appliance gains, lighting gains, and auxiliary equipment gains, is also plotted in Figure 3.15. The limitations of our behavioural representation are apparent here, with a 30% difference in the median results, and a far smaller range represented in the simulated electricity use. This is to be expected, since the model is not configured to produce consistently extreme behaviours, whereas one might expect some extreme behaviour in reality. There are a number of additional caveats to discuss which are likely to explain some extent of the discrepancy:

- There are differences in appliance and lighting use between countries within Europe. Using (ODYSSEE, 2009) for weighting the CEPHEUS data, one expects 27% lower use of appliances and lighting on average from a building in the CEPHEUS project to a UK home, for example.
- The dwellings built in the CEPHEUS project were fitted with the most efficient 'white' appliances of the time, whereas the Richardson et al. model uses a notional value which represents UK stock; such a difference was shown to be significant (up to 48% of the total energy use in European homes) by de Almeida et al.(de Almeida, Fonseca, Schlomann, & Feilberg, 2011).
- The character of domestic energy use has changed over the decade, and whilst European domestic energy consumption was at a slightly lower level in 2008 than in 2001, the proportion of electricity going to appliances was 8% higher (DECC, 2002), which could be reflected in this observed difference.

TABLE 3.1 – STATISTICAL SUMMARY OF THE UNIQUE HOUSEHOLD PROFILES GENERATED.

	Set-point °C	Appliance Gains kWh/m^2a	Lighting Gains kWh/m^2a	Airflow Gains kWh/m^2a	Occupancy Gains kWh/m^2a	Doors Frequency hrs/a
Max.	26	14.38	5.45	-1.77	5.58	29.8
Min.	16	6.19	1.97	-4.07	2.76	13.1
Mean	21.5	9.95	3.77	-2.72	3.82	20.1
Std. Dev.	1.70	1.62	0.74	0.52	0.49	3.36

Table 3.1 gives a statistical summary of the profiles as used by the thermal modelling software. Though the results are shown to reflect the average UK family, the output of Richardson's model is limited in that it does not represent extreme cases, nor does it include holiday periods. The mean number of hours of door opening is 20.1 $h.a^{-1}$, which is equivalent to 200 $s.day^{-1}$, and 300 to 130 $s.day^{-1}$ is the range generated respectively. It is not unlikely that households exist in which the doors are open for a far shorter, for housebound occupancy, or far greater, conceivably for a family with pets that use a garden.

3.4 A Regression Model of Occupant Behaviour's Effect on Energy Use

Now this section proposes a non-parametric regression model based on the IES VE simulation output, which will be used to determine the relationship between a number of variables attributed to occupancy and their effect on heating energy use. Such a model will also inform a simple model for determining the effect of a range of behaviour on the heating energy use of a household.

Parametric regression is a statistical analysis tool by which the effect of a known or unknown number of *predictor variables* on some *dependent variable* can be individually quantified with a degree of statistical significance. In its simplest form with one predictor variable, a one-dimensional linear regression model takes the familiar form of $y = mx + c$, in this case, for every x, y increases by a factor of m. The *estimator* (y) may have been found by a number of techniques, the most simple (and common) of which being ordinary least-squares (OLS) regression. OLS method describes a linear fitting method which treats each data point with equal weight, and minimises the sum-of-squares of the residuals in a function. OLS is widely used method for determining relationships between variables, and is the method by which IBM SPSS software will analyse data.

Figure 3.16 shows an example of a simple linear regression model. The data was generated by $Y = \frac{1}{15}X + C$, where C is a random number between 0-1[12]. With more data, one would get closer to is known to be the best fit, $y = \frac{1}{15}x + 0.5$. ε_i is the error introduced by the random element for point i. For simple OLS methods the aim is to minimise $\sum_i {\varepsilon_i}^2$.

[12] Random number generated by Microsoft Excel 2010 'RAND' function; algorithm based on (Wichmann & Hill, 1982).

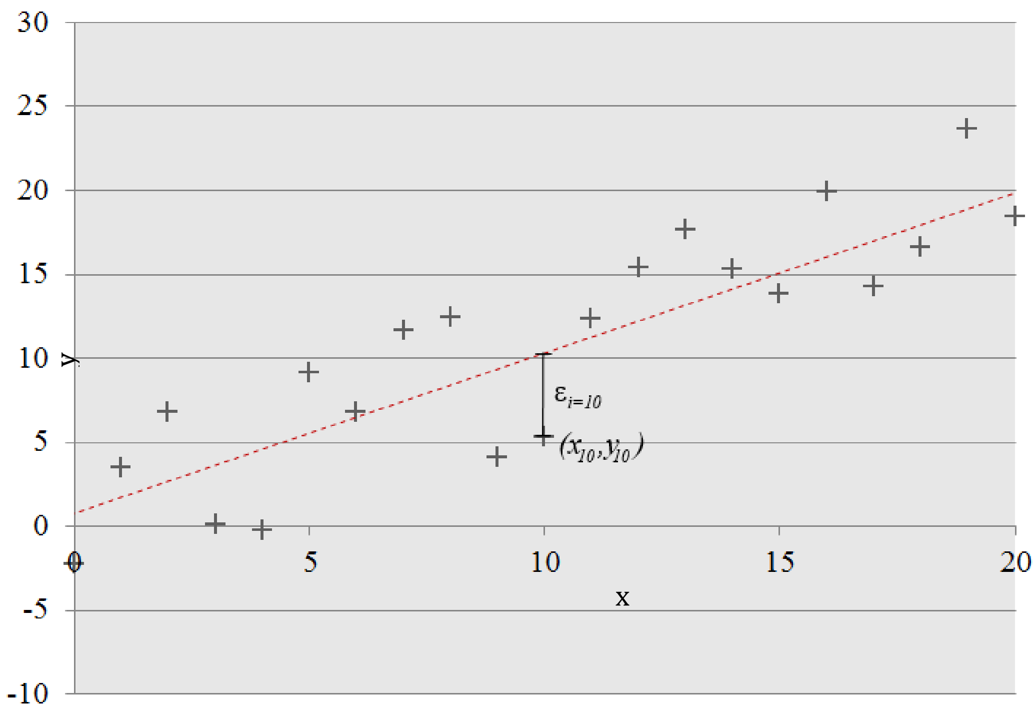

FIGURE 3.16 - EXAMPLE OF A LINEAR REGRESSION MODEL $y = 0.9527x + 0.8088$. THE DATA WAS GENERATED BY $Y = X + 10(C - 0.5)$.

Swan and Ugursal conducted a prominent review of building modelling techniques in 2009 (Swan & Ugursal, 2009), which details a number of regression models which have been successful in giving good estimates of relationships in the built environment (Al-Garni, Zubair, & Nizami, 1994; Andersen, Toftum, Andersen, & Olesen, 2009b; Howard et al., 2012; Raffio, Isambert, Mertz, Schreier, & Kissock, 2007; Ranjan & Jain, 1999; Tian & de Wilde, 2011; Tso & Yau, 2003).

Regression terms

For a multi-dimensional regression analysis given a data set $[y_i, x_{i1}, \dots, x_{ip}]_{i=1}^{n}$ of size n, and assuming linear relationship between the dependent variable y_i and the p-vector of the predictor variable x_{ij}, the model takes the form:

$$\boldsymbol{y} = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \tag{3.2}$$

where $\mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix}$, $\mathbf{X} = \begin{pmatrix} \mathbf{x}_1^T \\ \mathbf{x}_2^T \\ \vdots \\ \mathbf{x}_n^T \end{pmatrix}$, $\boldsymbol{\beta} = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_p \end{pmatrix}$, $\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}$, and $\mathbf{x} = \begin{pmatrix} x_{i1} \\ x_{i2} \\ \vdots \\ x_{ip} \end{pmatrix}$. ε_i is referred to as the error term, which captures all other factors not accounted for in the model which influence y_i. $\boldsymbol{\beta}$ is the p-dimensional parameter vector where β_i is the regression coefficient.

Certain assumptions are made about the data set when forming a non-parametric regression model. First, it is assumed that the system is not *heteroscedastic* or *multi-collinear*, and that the error terms are independent of each other.

- Heteroscedasticity – the variance of the dependent variable should display no dependence on the predictor variables, i.e. the predicted vs. actual variance in y_i is not randomly distributed. Heteroscedasticity is shown by any significant relationship on such a graph.
- Multicollinearity – any one predictor variable must not be directly or inversely proportional to another predictor variable i.e. $\mathbf{X}$ has a full *column rank*.
- Weak or no exogeneity – there is little or no random influence on the dependent variable.
- Linearity – a somewhat misleading term, the 'linear' regression actually implies that the parameter vector $\boldsymbol{\beta}$ has a linear relationship with the dependent, not the predictor variables themselves. Therefore polynomial expressions can be modelled.

When using regression analysis as a tool it is important to bear in mind that a significant correlation result does not imply a causal relationship, the two effects may be linked through some obscured mutual component; as Tufte commented:

"Empirically observed co-variation is a necessary but not sufficient condition for causality" (Tufte, 2003).

An example of an entirely causal relationship by definition is the Markov-Chain described in previous chapters. In the case of a Markov-Chain, the 'parent' variable X_0 of a variable X_1 effectively 'screens' X_1 from any other variables, except for further descendants. For more information on causality the author recommends (Hitchcock, 2012).

Methodology

We are interested in the differences between each model, therefore the differences in input variables including the appliance use, lighting use, occupancy gains from active occupants and sleeping occupants, set-point temp and door opening profiles. All other model parameters are either proportional to one of the factors above (e.g. room CO_2 concentration depends heavily on the level of occupancy, metabolic latent heat gains are directly proportional to the sensible heat gains), or are non-varying across models (i.e. weather data).

Setpoint temperature, °C (T)

This is the preferred setpoint temperature of the family, randomly assigned to each house, based upon a normal spread of temperatures measured in Passivhaus buildings across Europe. This independent variable is expected to be positive in sign and also to have a large absolute standardised coefficient, in every month.

Appliance and Lighting use, kWh (A, L)

These two variables are the total sensible heat gains from all internal appliance use and all internal lighting, in kWh. Since such gains are recouped in a Passivhaus, the coefficients are expected to be negative and substantial.

Airflow gains, kWh (F)

Heat gains (generally negative gains, i.e. losses) from window openings when room CO_2 and temperature reach defined limits are expected to be negative and low contributors to the model, due to the limitations of our approach to behaviour modelling.

Occupant gains, kWh (O)

Where persons are present in the building, they add associated sensible and latent heat gains into the rooms around them. Since in our occupancy the latent heat is a directly proportional to sensible heat, our causal predictor considers sensible heat only. One expects the coefficient to be negative and of equivalent size to the electrical gains, since the added sensible gains are no different.

Frequency of door opening (D)

Each change in occupancy results in a short period of door-opening, during which heat can escape the dwelling. A small positive correlation is expected.

TABLE 3.2 – DESCRIPTIVE STATISTICS OF INPUT VARIABLES FROM THE SYNTHESIS TECHNIQUES DESCRIBED PREVIOUSLY.

		Mean	Std. Deviation	N
Heating ($kWh\,m^{-2}a^{-1}$)	E_{jan}	5.118	1.220	100
Air ($kWh\,m^{-2}a^{-1}$)	F_{jan}	-.534	.1844	100
Occ. ($kWh\,m^{-2}a^{-1}$)	O_{jan}	.555	.1365	100

		Mean	Std. Deviation	N
App. $(kWh\,m^{-2}a^{-1})$	A_{jan}	1.473	.4727	100
Light. $(kWh\,m^{-2}a^{-1})$	L_{jan}	.591	.2083	100
Door. $(\min month^{-1})$	D_{jan}	180.33	60.73	100
Temp (°C)	T	21.48	1.711	100

Results & Discussion

SPSS statistics package was used to perform a regression analysis to estimate the coefficients associated with each variable introduced in the previous section, and to characterise the significance of the model. For each heating month a regression was forced for all causal predictors listed in Section 3.1 of this chapter, but subsequently a look at the significance of each variable indicated any that may not merit inclusion in the final model, either through a very low relative contribution to the final model or a low statistical significance. In this section the construction of the model is described, and then the final model is then presented along with the resulting regression coefficients.

It is obvious that, since the inputs using statistical methods, some amount of correlation between predictor variables is expected. If one were aiming to build a purely statistical model of the situation, then at the point of concern about covariance between variables arising, a factor analysis could be used to define a new set of independent variables. In the case of this study this approach is not taken, as the end model should have simple inputs based on the real factors at play within the dwelling, rather than abstracted variables. The decision was taken to only use methods which eliminate non-significant variables from the model by a stepwise regression analysis with a probability to remove of $F \geq 0.100$, where F is the variance between groups over the variance within a group, or the unexplained variance over the explained variance, see any good statistics text for more information, such as Lomax (Lomax & Hahs-Vaughn, 2012).

As each variable is forced into a regression model for each month, the significance and contribution of each parameter is measured for each month. An example for January is shown in Table 3.3.

TABLE 3.3 - CORRELATIONS BETWEEN VARIABLES FOR AN INITIAL 'FORCED' REGRESSION.

		E_{jan}	F_{jan}	O_{jan}	A_{jan}	L_{jan}	D_{jan}	T
Pearson Correlation	E_{jan}	1.000	.042	-.343	-.385	-.230	-.111	.876
	F_{jan}	.042	1.000	-.695	-.426	-.375	-.423	-.106
	O_{jan}	-.343	-.695	1.000	.637	.594	.285	-.074
	A_{jan}	-.385	-.426	.637	1.000	.481	.080	-.080
	L_{jan}	-.230	-.375	.594	.481	1.000	.032	.054
	D_{jan}	-.111	-.423	.285	.080	.032	1.000	-.088
	T	.876	-.106	-.074	-.080	.054	-.088	1.000
***p*-value (1-tailed)**	E_{jan}	.	.341	.000	.000	.011	.136	.000
	F_{jan}	.341	.	.000	.000	.000	.000	.147
	O_{jan}	.000	.000	.	.000	.000	.002	.232
	A_{jan}	.000	.000	.000	.	.000	.214	.214
	L_{jan}	.011	.000	.000	.000	.	.375	.297
	D_{jan}	.136	.000	.002	.214	.375	.	.192
	T	.000	.147	.232	.214	.297	.192	.

The significance, or p-value, of each predictor variable is an indicator of the statistical likelihood of occurrence, i.e. the likelihood of a null hypothesis. In preliminary variable tests, the frequency of door-opening (D) was shown to lack statistical significance. Using a probability-to-remove of $F \geq 0.100$, D was consistently removed from the model. While other variables also failed to show significance for some months, D was the sole consistent variable achieving this, and so all other variables were forced into the final model.

The following parameters were treated as causal predictor: the set-point temperature (T), electricity usage for appliances and lighting (A & L, respectively), airflow gains (F), and occupant sensible heat gains (O).

Autocorrelation Test

Autocorrelation is the cross-correlation of a varying parameter with itself. Normally an important attribute in signal processing - in our case it is worth checking that there have been no calculation errors in the process thus far which have ended up with interdependencies in the outputs. Options to test for autocorrelation include:

- The Durbin-Watson value, to check for the presence of first-order autocorrelation
- The Breusch-Godfrey test, an auxiliary regression analysis used for time series with lags of the dependent variable

Since no impactful series lags are anticipated in the modelling results (the data is at a monthly resolution), the Durbin-Watson value d is used. d is given by (3.3) where ε_i is the i^{th} residual in a series of N values. d is in the range $0 \leq \mathrm{d} \leq 4$. A value of $\mathrm{d} = 2$ would infer zero autocorrelation, while $\mathrm{d} << 2$ or $\mathrm{d} >> 2$ infers evidence of a positive and negative autocorrelation respectively. Strong evidence of a correlation depends upon N and the number of variables in the regression model. Strong evidence for autocorrelation in the models presented here would be d values of < 1, so while Table 3.4 shows a range of values between 1.1 and 1.7, autocorrelation is unlikely to be a significant issue within the synthesised or simulated data.

$$d = \frac{\sum_{i=2}^{N} (\varepsilon_i - \varepsilon_{i-1})^2}{\sum_{i=1}^{N} \varepsilon_i^2} \qquad \textbf{(3.3)}$$

TABLE 3.4 - THE DURBIN-WATSON VALUES FOR EACH REGRESSION MODEL

Model	Jan	Feb	Mar	Apr	Oct	Nov	Dec	Sum
Durbin-Watson Value	1.730	1.252	1.111	1.505	1.696	1.316	1.758	1.196

Heteroscedasticity Test

Heteroscedasticity is an important property of the model to analyse: if heteroscedasticity is strongly present in a given set of data, then there is a clear indication that the model is not describing the situation to its full extent. Either there is a missing or a superfluous term. Is real terms, a display of heteroscedasticity indicates that the expected variance is not followed by the observed variance, and therefore something lies unaccounted for in the model – perhaps a has a polynomial dependence on some parameters rather than linear.

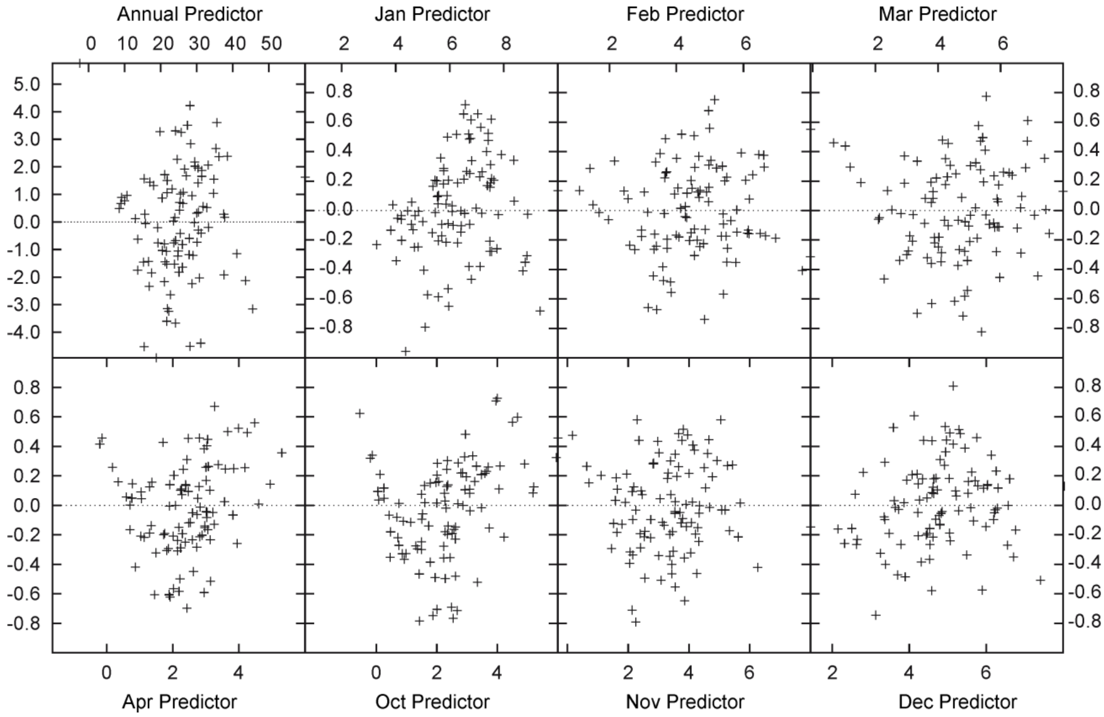

FIGURE 3.17 - RESIDUAL VS. PREDICTOR PLOTS FOR THE SUMMED-ANNUAL (TOP-LEFT FRAME) AND MONTHLY REGRESSION MODELS FOR TESTING OF HETEROSCEDASTICITY. FIGURE REPRINTED WITH PERMISSION FROM COPYRIGHT HOLDER (BLIGHT & COLEY, 2013).

With each monthly regression model, SPSS was programmed to output the Regression Standardised Residual plotted against the Regression Standardised Predicted Value. The results can be seen in Figure 3.17 for the 7 individual month's predictors, and for the aggregate model predictor (top-left).

The annual heteroscedasticity test appears negative, with no determinable trend in the variance around the residual value. However, the same cannot be said for the figures plotted for each month – a slight trend emerges as the warmer months of April and October are approached which resembles a polynomial term coming into play.

Since the trend is strongest in the warmest months, and the regression model otherwise represents the data well, the evident heteroscedasticity has been ignored at this juncture.

Model Results

Each variable is aggregated into monthly and annual totals, denoted by the subscripts y and m respectively. (3.4) presents the suggested multivariate linear regression model for the yearly aggregated energy, E_{ya}, while the monthly model for annual energy E_{ma} is presented in (3.5).

$$E_{ya} = \gamma_0 + \gamma_1 T + \gamma_2 A + \gamma_3 L + \gamma_4 F + \gamma_5 O + \varepsilon_{tot} \quad \textbf{(3.4)}$$

$$E_{ma} = \sum_m E_m + \varepsilon_{ma} \quad \textbf{(3.5)}$$

$$= \sum_m (\mu_{0_m} + \mu_{1_m} T_m + \mu_{2_m} A_m + \mu_{3_m} L_m + \mu_{4_m} F_m + \mu_{5_m} O_m) + \varepsilon_{ma} \quad \textbf{(3.6)}$$

where γ_0 and μ_0 are the regression model intercepts, γ_j and μ_j are the regression model coefficients ($j = 1, 2, 3, 4, 5, 6$), m is the month of the regression model ($m =$ January, February, March, April, October, November, December), ε_{tot} is the standard regression error for the annual regression model, and ε_{ma} is the root-sum-square of the monthly regression standard errors, by principles of error summation.

TABLE 3.5 - RESULTS OF THE MONTHLY-MEAN REGRESSION ANALYSIS FOR THE DEPENDENT VARIABLE: HEATING ENERGY PER METER-SQUARED PER ANNUM ($\boldsymbol{kWh.m^{-2}a^{-1}}$). SIGNIFICANCE LEVELS INDICATED BY * <.050; ** <.005. †: SUM OVER HEATING PERIOD ($\boldsymbol{kWh.m^{-2}a^{-1}}$).

Monthly-mean regression model		Unstandardised Coefficients		Standardised Coefficients
		γ	Std. Error	β
Constant	γ0	-55.631	4.466	
Set-point (°C)	γ1	4.334	.181	.893**
Appliance Gains †	γ2	-.396	.207	-.078*
Lighting Gains †	γ3	-.720	.376	-.060*
Airflow Gains †	γ4	-1.269	0.796	-.080
Occupancy Gains †	γ5	-1.645	.876	-.097*

Table 3.5 shows the results of the linear regression model for the aggregated annual data. The unstandardized coefficients are denoted by γ, the standard error is included, and the standardised coefficients are listed under β.. The standardised coefficients are found by dividing the 'distance from the mean' by the standard deviation of each variable, and can be used to directly compare the relative contributions from independent factors.

All remaining causal predictors in Table 3.5 have their expected sign. A strong dependence on set-point temperature is shown, almost 10 times the contribution to the heating energy than the other predictor variable standardised coefficients. Occupancy gains show the next highest contribution, roughly 20% higher than the airflow and appliance gains. Lastly the lighting gains come in at 40% lower contribution than the occupancy gains. This may be due to the lighting model being dependent on not just occupancy but on external irradiance (Richardson et al., 2009), as described in Part 1. Each of the results has a p-value of less than 0.050, aside from the airflow variable, which is under 0.100. On the whole, the annual model does a very good job of recreating the simulation results, accounting for more than 90% of the variation in every case assessed. The effect in each case can be calculated using the values found in Table 3.2.

The resulting model gives a good correlation to the simulated output, as shown in Figure 3.18. The series is followed quite accurately by the regression model, including in the upper and lower 5%, within the bounds of standard error. A Kolmogorov-Smirnov test indicates the two datasets are not significantly different.

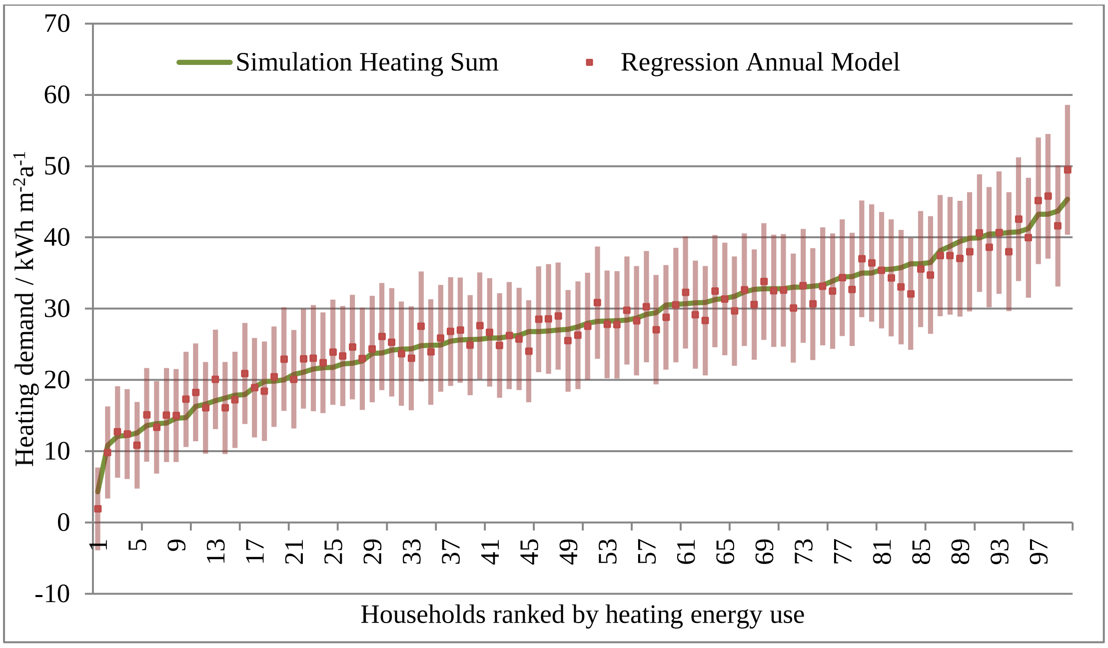

FIGURE 3.18 - REGRESSION MODEL HEATING ENERGY RESULTS PLOTTED AGAINST THE SIMULATED RESULTS.

The monthly models are a more precise way to measure the effect of each predictor variable, as they provide finer detail where external temperatures are less varied; the coefficients obtained from these monthly models differ significantly, and this is thought to depend somewhat on the external conditions having changed.

The above regression estimates were based on the sum of monthly-mean heat demand and losses. Because losses from regulated (mechanical) and non-regulated (natural ventilation, infiltration) airflows are related to the internal-external temperature difference and the synthetic behaviours are implicitly linked to the month of the year, better performance would be expected from a regression model which allows incorporation of monthly-mean temperatures.

The coefficients are plotted against the monthly-mean temperature, on which some variables displayed a linear dependence, as seen in Figure 3.19. A clear trend is visible in the heating set-point coefficient (μ_1), with it being negatively proportional to rise in external temperature. The coefficients for airflow gains (μ_4) display the same trend, while the appliance use and the constant coefficients (μ_2, μ_0) show the opposite trend.

TABLE 3.6 - RESULTING COEFFICIENTS ($\boldsymbol{M}$) AND INTERCEPTS ($\boldsymbol{C}$) FOR EACH PREDICTOR VARIABLE IN THE TEMPERATURE-DEPENDENT REGRESSION ANALYSIS, INCLUDING ERROR TERMS.

	μ_0	$\delta\mu_0$	μ_1	$\delta\mu_1$	μ_2	$\delta\mu_2$	μ_3	$\delta\mu_3$	μ_4	$\delta\mu_4$	μ_5	$\delta\mu_5$
M	-.670	.113	.015	.005	.000	-	.000	-	.012	.134	.081	.035
C	-5.97	.024	.574	.024	-.639	.024	-.777	.024	-.850	.607	-1.38	.157

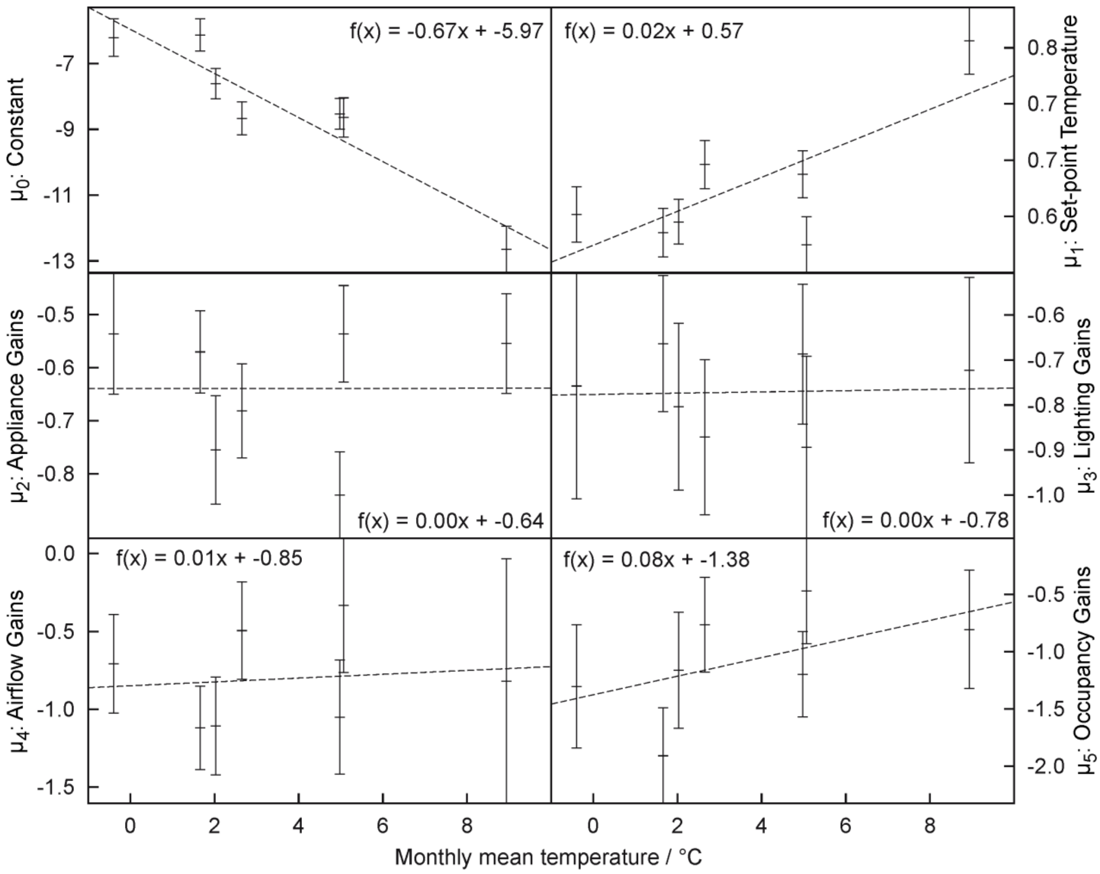

FIGURE 3.19 - COEFFICIENTS OF LINEAR REGRESSION PLOTTED AGAINST MEAN MONTHLY EXTERNAL TEMPERATURE, WITH STANDARD ERROR BARS INCLUDED. EACH DATA-POINT AND BAR REPRESENTS ONE MONTH OF THE HEATING SEASON. ALSO INCLUDED ARE LINEAR FITS GIVING THE GRADIENT AND CONSTANT FOR THE COEFFICIENTS OF THE TERMS IN THE FINAL REGRESSION EQUATION, AS SEEN IN TABLE 3.6.13

(3.7) gives the modified temperature-dependent regression model coefficients, using the linear dependence components introduced in Table 3.2.

$$\mu_{j_m} = (M_j \pm \delta M_j)\bar{T}_{ext_m} + C_j \pm \delta C_j \tag{3.7}$$

with

μ_{j_m} modified coefficients for j = 1, 2, 3, 4, 5,6 and m equal to respective month / period

M_j proportional component of coefficient j

C_j constant component of coefficient j

δC_j standard error in constant component of coefficient j

[13] Figure reprinted from (Blight & Coley, 2013) with permission from Copyright holder.

δM_j standard error of respective coefficient j, and

$\bar{T}_{ext_m}$ mean external temperature for given month / period.

Using (3.5) in conjunction with (3.7) the impact of various scenarios can be investigated. Suppose all variables are kept at their monthly-mean value and this method is used to calculate the overall effect on the total heating required while one variable at a time is modified. Table 6 shows the results of such a calculation. Modifiers of one standard deviation (+1σ), +10%, +100%, and -50% are given. The relative standard deviation serves as an indication of the variance of the predictor. Due to the linear nature of the regression, an increase is related to a decrease by $\delta x = -1 \times -\delta x$. It is noted that this model is not an accurate representation, many of the variables hold non-linear relationships, it should be treated as a rough guide or 'rule-of thumb', and extended not beyond one standard deviation of the relevant variable.

TABLE 3.7 - PERCENTAGE AND VALUE CHANGE IN REQUIRED ANNUAL HEATING ENERGY WHEN MODIFYING VARIABLES BY ARBITRARY AMOUNTS.

Modification	+ 1σ		+10%		+100%		-50%	
	%	Abs	%	Abs	%	Abs	%	Abs
Set-point °C	30.1	-7.48	37.9	-9.43	379.2	-94.3	-190	47.2
Appliance Gains ($kWh\, m^{-2}a^{-1}$)	-4.2	1.04	-2.6	0.64	-25.6	6.36	12.8	-3.18
Lighting Gains ($kWh\, m^{-2}a^{-1}$)	-2.1	0.54	-1.1	0.27	-10.8	2.69	5.4	-1.35
Airflow Gains ($kWh\, m^{-2}a^{-1}$)	1.7	-0.42	0.9	-0.22	8.9	-2.22	-4.5	1.11
Occupancy Gains ($kWh\, m^{-2}a^{-1}$)	-2.1	0.53	-1.7	0.42	-16.7	4.15	8.3	-1.91

Set-point temperature evidently has the largest impact on annual heating energy use, with a 1σ increase giving a 30 % increase in heat used, or an additional 7.48 $kWh.m^{-2}a^{-1}$ heating for the average household. The +100% and -50% modifications of the set-point temperature would represent very extreme behaviours (~40 °C and ~10 °C respectively); while the lower end may represent an unoccupied building, the upper end is an unrealistic indoor set-point. However these are not unrealistic modifications to some of the other predictor variables. With a doubling in appliance use, one expects using these results a reduction of 26% in heating energy.

Airflow is a more complex variable, as the heat lost through an open doorway is wholly dependent on the external and internal conditions at the time. A doubling in airflow gains would cause roughly 9% higher energy use for the average household modelled here. As discussed previously, our representation of airflow may be too simplified when compared to the wide range of behaviours related to window opening in the home.

From the results the following 'rules of thumb' can be drawn as examples:

- The set-point temperature necessary to reach zero heating energy ($E_{total}=0$) is 15.8 °C, or 0.74 times the average set-point temperature of 21.5 °C.
- The gains from electric appliances and lighting required to negate the heating energy is 49.2 kWh.$m^{-2}a^{-1}$. This is much greater than the average total space-heat requirement, which indicates only that such gains are not fully utilised due to there being a difference in phase between heat requirement and appliance-use.
- Sensible gains from occupants would need to increase by a factor of 7 to negate the use of heating while maintaining an average temperature of 21.5 °C.

These values are not generalisable, as they are extrapolations of co-dependant relationships derived from a single architecture; however they are likely to be approximately correct for many passive houses, particularly in their relative ordering.

3.5 Behavioural Simulation Conclusions

It has been shown that it is possible to generate varied and representative models of typical UK occupancy patterns and appliance-use behaviour in homes, and to use these within a modelling environment. The simulation of households has been shown to reproduce measured data surprisingly well. Due to the need to create such as large number of profiles the method is clearly not suited to general use unless it is embedded within the interface of industry standard software. However, there is no reason that this could not be done in some form and the resulting technique would go some way to reducing the credibility gap that models and modellers suffer from.

In order that others need not complete multiple runs with a spectrum of behaviours for any and every project, and to allow the generation of 'rules of thumb' about the sensitivity of Passivhaus designs to variation in use, a regression model was assembled. In the regression analysis set-point temperature, appliance-use, and airflow behaviour were shown to be the major estimators of total heating energy. Occupancy patterns were shown to be less significant factors. The regression model is limited to a single architectural design and hence it would be useful to examine how much the values of its coefficients change for other Passivhaus dwellings. However it is clear that many of the concerns that some have voiced about the Passivhaus approach being overly sensitive to occupant behaviour and therefore not applicable to many sections of society would appear to be unfounded.

Behavioural Simulation Summary

The effect of occupant behaviour on the energy use of a dwelling is highlighted in Part 1, along with the lack of understanding and measurement of this effect. In this part of the thesis, two key outputs have been studied, both using on the work undertaken by Richardson *et al*. to develop a domestic occupancy, lighting and electricity use model which is representative of a UK household (Richardson, Thomson, et al., 2010; Richardson et al., 2008, 2009).

The first aspect concerns the development of a stochastic occupancy and internal heat gain generator, which can output high-resolution profiles representative of a single UK household – rather than an average of many. This allows for more diverse resulting profiles and what one may consider atypical representations of occupancy and appliance use.

The second aspect is on the development of a regression model based on the results of the first. This model shows the weighted contributions of setpoint temperature far exceeded the influence of variant occupancy or internal gains, which in comparison were low contributors to expected energy usage for heating. A formula for heating energy demand is developed based on the results of modelling 100 Passivhaus dwellings, which is shown to align with measured data well.

The results are not without limitations however – the modelling done was based on a single form of house, with set physical conditions. – the work does not explore different forms and constructions. In addition, the heating demand was modelled using rudimentary modelling of the heating setpoint - a constant criterion from October to April. This is shown in reality to be a very different picture, with many determinants (Wei et al., 2014). This is further discussed in Part 1.

Part 4 Case Studies in Social Housing

Exeter City Council have made the decision to build only Passivhaus standard social housing and care facilities in an effort to lead the way in city council sustainable building. Access was granted to contact the invited tenants prior to their moving into new Passivhaus dwellings at two locations in central Exeter. The two-phase survey methodology introduced in Section 2.3 is designed to assess the environmental attitude and measure perceived behaviour of the perspective tenants, and return at a later date (a minimum one full year after moving into their new dwellings) to ask the same questions. In this way the behaviour and attitudes of occupants is assessed at two reference points, highlighting any correlated changes.

Data was collected via a number of means – initially Exeter City Council introduced the survey to the occupants in correspondence and at the open day for the housing. Letters were also sent round to occupants who were not able to attend the open day. After a year had passed, Phase 2 began and letters were sent to arrange the follow-up interviews.

Phase 1 of the data collection went well, with 18 of 21 total households interviewed. Phase 2 organisation was less successful however, with only one response to the 21 letters sent. The remainder of the interviews were conducted by cold-calling at the homes of the residents. A total of 8 respondents were interviewed, 6 of which were also interviewed in Phase 1 (6 of 18).

Quantitative analysis of the results was deemed statistically inviable, therefore the results of analysis should be treated with caution and any correlated indicators viewed as anecdotal.

4.1 Data Collection

Pilot Surveys – Phase 1

The residents had moved into Rowan House in January 2011, and the Phase 1 pilot survey was conducted in February, shortly after moving in. For this reason, the residents were asked to think back to their previous property when answering Section 1 of the survey.

The full interview audio was recorded to capture any answers to open-ended questions or other qualitative details that were vocalised. The initial responses to the survey led to the minor re-wording of questions which were identified as vague, specifically P1 Q17:

Please indicate which setting you keep the radiators / heaters on?

altered to:

Please describe which settings you keep the radiators / heaters on during the heating season?

and P1 Q48a (P2 Q33a):

How often do you try to conserve energy?

altered to:

How often do you, through meditated action or inaction, try to conserve energy?

The changes were applied within the pilot study (the interviewer rephrased the questions on the day and therefore any incoherence was not seen in the results), and so the Phase 1 pilot results are able to be integrated into the main body of results.

Pilot Surveys – Phase 2

The Phase 2 pilot survey indicated no questions which were unclear or required alteration, therefore the Phase 2 pilot survey matched the Phase 2 main survey.

Implementation of the surveys

Method for data collection

The prospective tenants were told by ECC at the open day visits to Knights Place that they would be required to meet with the author to arrange a time for interview. This was not stipulated contractually, as it would have created legal work deemed unfeasible by ECC. The interviewer was present at two open days to meet prospective tenants, where two of the Phase 1 interviews took place. Letters were then sent out to each of the occupants, requesting a meeting to be arranged to conduct the survey.

The response rate to these letters was low (2/16), and so a 'cold-calling' approach was adopted, where a letter would be sent to inform the occupant that the interviews were taking place on-site on a certain day, on which day a visit would occur. Phase 1 took place in January 2011 at Rowan House, and June-September 2011 at Knight's Place.

Phase 2 consisted of a very similar method (letters followed by site visits), however due to the low success rate with a letter pre-warning the occupant, unscheduled visits ('cold calls') were used to collect the majority of the Phase 2 responses.

Response rate discussion

The response rate to Phase 1 of the surveys was 3/3 properties in the pilot group and 8/18 properties in the main group, totalling 52%.

The response rate for Phase 2 was much lower than hoped, with 2/21 letter respondents, 4/19 successful 'cold calls', 6/21 in total being interviewed.

Reasons for this low level of response are suggested below:

- The period of time that elapsed between Phase 1 and Phase 2 – in the majority of cases this was just over one year, however for 50% of Phase 2 respondents the duration was closer to 15 months. This time discrepancy is unlikely to affect the responses to the survey, however at least two households had since moved to other accommodation since Phase 1 interviews took place.
- Many of the tenants referenced poor community coherence and a "very negative atmosphere" within the development. This seemed to stem from two areas – firstly there were descriptions of certain residents displaying antisocial behaviour (noise and aggression); and secondly, a lack of car-parking spaces (designed to be 10 spaces for 18 residents at the larger site, with further on-street parking[14] available down a steep driveway) meant that relations between residents were further strained.
- There were a number of post-occupancy build quality issues, which some residents considered to be poorly handled by the City Council Housing Team. It is feasible that these difficulties may have led to an uncooperative attitude to the letter due to a council logo being present on

[14] Where on street parking in the area was already a contentious issue, see (Sanders, 2009)

the correspondence. On a number of occasions the author was taken as working for the council, despite introductions.

Cold calling was comparatively more successful, with two-thirds of the residents present at the time of calling accepting the invitation for interview either immediately or at a later time/date.

4.2 Analysis based on the importance of the environmental credibility of scheme

There are a large number of ways in which the analysis could be discussed. For ease of discussion, the group of tenants that were interviewed have been split into two groups of three:

- **Group A - those for whom the environmental credibility of the scheme was an important factor, and**
- **Group B - those for whom it was an unimportant factor.**

This was based on the tenants answer to one question specifically -

Question 40: How important a driver was the Passivhaus Certification of your new home in deciding to move?

The metric was chosen to compare those households who had responded highly (≥ 3/5 on a Likert-type scale) to the environmental credos playing a large role in their moving were grouped into Group A, against those for whom it was not an important factor in their decision to move (< 3/5) gathered in Group B, i.e. Question 40 as above.

Of these categories there are three households in each that had been interviewed either before or at the beginning of their term, and again after at least one full year.

It happens that this grouping exhibits strong intro-group correlations, for example, Group A disclose a much higher Phase 1 average winter energy spend than those in Group B (£95/month vs. £29/month), and those in Group B were generally in much smaller properties than Group A, before moving into the new developments. Each section of both phases of the survey will be examined using this grouping below.

Demographics and previous properties

It is of interest to understand the previous housing types of the residents, recorded in the tables below.

TABLE 4.1 – ANSWERS TO A SAMPLE OF QUESTIONS REGARDING PREVIOUS PROPERTY IN SECTION 1 OF PHASE 1 INTERVIEWS, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)			Group B (n=3)		
Previous Property Type	Double terrace house	semi-detached house	beach cottage	Flat	Flat	Tent
Energy spend per heating month	£105	£45	£135	£45	£15	£15
Heating control usability	Easy	Difficult	Difficult	Easy	Easy	Easy
Usage duration	6 months a year heating average			Average two month use of heating season per annum (though cooking stove was the heating system for the tent, counted as 0)		
Night vent. preferences	Like to sleep with windows open			None specified		
Soft flooring preferences	Yes	Yes	Yes	Yes	No	No

Demographics

TABLE 4.2 - ANSWERS TO A SAMPLE OF DEMOGRAPHICS QUESTIONS IN SECTION 3 OF PHASE 1 INTERVIEWS, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)			Group B (n=3)		
Occupation	Retired/ working part-time	Retired	Retired & unable to work	Unemployed	Unemployed	unable to work
Qualifications	Vocational	Vocational	None	None	Secondary	Vocational
Income	£10-15k			£5-10k		
Occupancy	0.88 average			0.54 average		

Arguably, the demographics and previous households indicate that Group B, with smaller living spaces and lower household income, may score lower on a Socio-Economic Position (SEP) scale such as that proposed by others/ (Galobardes, Shaw, Lawlor, Smith, & Lynch, 2006; Oakes & Rossi, 2003). SEP was not a measure designed into this survey, and although it is possible to devise a rudimentary analysis, it is not further considered.

Phase 1

Current energy use estimates

TABLE 4.3 - ANSWERS TO A SAMPLE OF QUESTIONS IN PHASE 1 INTERVIEWS, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	Group B (n=3)
Average Annual heat spend	£645	£70
Shower use (min/week)	70	70

Group A are seen to spend a vastly higher amount on heating on average through the heating season, however the estimated average showering time per week was the same. Regarding showering, T02 PRE:

"As long as water's there, I'm comfortable – it's heaven in there!"

Use of windows/ventilation

Responses to ventilation use are shown in the table below. It is clear that on average more windows are regularly used for ventilation by Group A than Group B, and Group B preferred less night ventilation.

TABLE 4.4 - ANSWERS TO A SAMPLE OF VENTILATION QUESTIONS IN PHASE 1 INTERVIEWS, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)			Group B (n=3)		
No. windows regularly opened & closed	4			2		
Night ventilation	Yes	Yes	Yes	Yes	No	No

T03 PRE ***"I'd have the extractor fan on and the kitchen window open... There's always an window open in the bedroom - I have to have fresh air"***

T01 PRE ***"I have my bedroom window open the whole time, I can't sleep without it. It's important to have fresh air through – especially with (a dog)."***

User expectation

All tenants displayed high expectations with the same scores and deviations across both groups.

TABLE 4.5 – EXPECTATION LEVEL OF NEW HOME, AS INDICATED ON LIKERT SCALE, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	Group B (n=3)
Expectations from new home	High 4.67(.42)	High 4.67(.42)

T01 PRE ***"Hoping it'll be a lot cheaper."***

T03 PRE ***"(We expect it will be) ...about 10,000 times better"***

Environmental behaviour score

There appears to be a lower environmental scoring on average in Group B, however note the standard deviations are quite high regarding litter and petrol use, indicating a range of responses within the group.

TABLE 4.6 – ENVIRONMENTAL SCORES AS INDICATED ON LIKERT SCALE, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	Group B (n=3)
Recycling	4.33 (.58)	2.44 (.51)
Litter	4.0 (1.0)	3.3 (1.5)
Petrol	4.33 (.58)	4.33 (1.15)

Environmental concern score

TABLE 4.7 – ENVIRONMENTAL CONCERN SCORES AS INDICATED ON LIKERT SCALE, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	Group B (n=3)
Concern	4.67(.42)	4.67(.58)

T02 PRE ***"It's something new, and I'm all for this, we're not going to be on the shelf much longer but there's an awful lot of people like you and our grandchildren who are going to be, so we could 'do our bit' now."***

Social normalisation score

TABLE 4.8 – SOCIAL NORMALISATION SCORES AS INDICATED ON LIKERT SCALE, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	Group B (n=3)
Others personal effort	4.33 (.58)	3.33 (.58)
Others personal approval	4.33 (.58)	2.67 (.58)

T03 POST (on others saving energy) ***"Probably not as much as they could, judging by the way some of them leave their lights on at night, and radios... It's not fair on the rest of us trying to save energy."***

Reasons to conserve energy

TABLE 4.9 – ENERGY CONSERVATION SCORES AS INDICATED ON LIKERT SCALE, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)	**Group B (n=3)**
Economic	3.0 (1.0)	4.0 (.0)
Environmental	3.0 (1.0)	2.66 (.58)
Social	3.0 (1.0)	2.33 (.58)

Phase 2

In the tables presented below, the convention is used whereby:

- a positive variation from Phase 1 will be shaded green, and
- a negative variation will be shaded pink.
- In addition, an arrow is also included to indicate the direction of shift, if any.

How are the tenants using the home?

TABLE 4.10 – SAMPLE ANSWERS FROM SECTION 1 OF PHASE 2 SURVEY, SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)			**Group B (n=3)**
Avg. thermostat setting °C	19.8 (.29)			18.2 (1.76)
Window use	All opening some windows when hot and when pets outside			One flat regularly opening windows in 3 rooms
MVHR use	Used	Used	Not used	Used
Comfort level	slightly too warm			good
Comfort compared to previous dwelling	3.58 (.14)			3.50 (1.32)
Perceived control over thermal environment	3.67 (1.53)			4.33 (1.15)

What is their current energy use?

TABLE 4.11 – ESTIMATED ANNUAL FUEL SPEND IN PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)		Group B (n=3)	
Annual fuel spend	£372	↑	£504	↓
Shower use (min / week)	41 (26)	↑	72 (33)	-

Phase 1 - Phase 2 comparison – Group A demonstrating lower energy spend, and estimate less time spent showering. Group B are now spending more on energy than previously, time spent showering constant.

T06 POST ***"When first offered these flats we were told they were a lot cheaper than they are to run. They're not bad, just not as cheap as expected."***

T04 POST ***"All-in-all, I'm paying more here than I was there."***

How do they currently use windows/ventilation?

TABLE 4.12 – WINDOW USAGE IN PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)		Group B (n=3)	
Windows open	Regular	-	Irregular	↑
Reasons for regular window use	Pets	-	None	↑

Phase 1 - Phase 2 comparison: Group A - little change in window behaviour. Group B – seem to have adopted PH ventilation strategy.

T04 POST ***"You can't hear anything with the windows shut. The place is so well sealed; it's like living in a tomb. You can hear nothing. It's quite disconcerting actually."***

Were expectations met?

TABLE 4.13 – EXPECTATION RESPONSES FROM PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)		Group B (n=3)	
Thermal environment	5.0 (0.0)	↑	3.67 (2.31)	-
Air quality	4.0 (1.73)	↑	4.33 (.58)	↑
Usability	4.0 (0)	↑	1.50 (0.71)	↓

Phase 1 - Phase 2 comparison: Group A have seen their expectations about comfort, air quality and system usability met, whereas Group B shows lower satisfaction than expected with usability of heating systems.

T04 POST ***"Something seriously gone wrong with it – I feel misled."***

T05 POST ***"Whole world of difference. Energy costs are nominal."***

Environmental behaviour score

TABLE 4.14 – ENVIRONMENTAL BEHAVIOUR RESPONSES FROM PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A (n=3)		Group B (n=3)	
Recycling	4.56 (.77)	-	2.56 (.84)	-
Litter	3.33 (2.08)	-	3.33 (1.52)	-
Petrol	4.0 (1.73)	-	n/a	-

Phase 1 - Phase 2 comparison: not much change, slight decrease in environmental behaviour score in group A – but not significant.

T02 PRE ***"Never did, but it's changed now, I'm a freak now with saving energy, [I'm always] flicking switches."***

Environmental concern score

TABLE 4.15 – ENVIRONMENTAL CONCERN SCORE FROM PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A		Group B	
	4.47 (0.92)	-	4.53 (.64)	-

Phase 1 - Phase 2 comparison: Very slight lower scores in environmental concern than pre-occupation.

Social norm score

TABLE 4.16 – SOCIAL NORMALISATION RESPONSES FROM PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A		Group B	
Importance of other's effort	3.33 (2.1)		4.67 (.58)	
Perceived others personal effort	3.67 (1.15)	↓	2.67 (.58)	↓
Perceived others personal approval	4.33 (1.15)	-	3.0 (1)	↑

Phase 1 - Phase 2 comparison: A & B the feeling that others not putting in a lot of effort has increased.

T04 POST *"Some are nice here and make an effort to be friendly, others don't - they're just trouble makers."*

T06 POST *"Very negative community atmosphere."*

Reasons to conserve energy

TABLE 4.17 – REASONS FOR CONSERVING ENERGY RESPONSES FROM PHASE 2 (AFTER ONE YEAR), SPLIT BY GROUP A (ENVIRONMENTAL CREDOS IMPORTANT FACTOR IN MOVING HOUSE) AND GROUP B (ENVIRONMENTAL CREDOS NOT IMPORTANT FACTOR IN MOVING HOUSE).

	Group A		Group B	
Economic	2.67 (1.15)	↓	2.67 (.58)	↓
Environmental	3.33 (.58)	↑	3.33 (1.15)	↑
Social	3.0 (1)	-	3.0 (1)	↑

Phase 1 - Phase 2 comparison: In both groups economic reasons for saving energy have devalued, and environmental reasons have increased in value.

Case Studies in Social Housing Summary

In this research a number of social housing tenants have been surveyed over the transitional move into a new-build Passivhaus apartment. The tenants' environmental behaviour, environmental concern, and expectations and apprehensions about living in a low-energy home have been recorded through two structured surveys and a semi-open interview format (Phase 1). The tenants have then been revisited approximately one year after the move-in date, for recording if and how these measures may have changed throughout the group (Phase 2). The Phase 2 survey response rate was rather low with only 6/18 Phase 1 respondents surveyed.

This low response rate leads to a question – is six responses enough for a meaningful quantitative analysis? Quantitative analysis of the results was deemed statistically inviable, therefore the results of analysis should be treated with caution and any correlated indicators viewed as anecdotal only.

The attitude- and behavioural-responses to the survey were analysed using a grouping of those for whom the environmental aspects of the development are of large importance to moving, and those for whom it was not an important factor. The results give some interesting group correlations, such as similar intra-group attitude

Part 5 Summary and Reflections

5.1 Simulating occupant behaviour variance

Summary

Literature demonstrates that occupant behaviour is one of the most significant of building energy performance determinants, yet is poorly understood– this is shown to be a contributing factor to the considerable discrepancies between building energy usage in design and its measured performance. A better understanding of occupant behaviour's impact on building energy use (and therefore a better understanding of this performance gap) is crucial to reduction of CO_2 emissions from the building stock, in line with UK Government targets.

This thesis describes the development of a methodology which generates stochastic occupant behaviour profiles based on recorded time-use data in the UK, using a modified form of a third-party tool. These profiles include occupancy level, equipment gains, and lighting gains. In conjunction with temperature data measured in Passivhaus buildings and a simple model of window opening, these profiles were used to model a large number of buildings in dynamic thermal simulation software.

A regression model was defined in order that others need not complete multiple runs with a spectrum of behaviours for any and every project, and to allow the generation of 'rules of thumb' about the sensitivity of Passivhaus designs to variation in use. The output of this regression analysis shows that set-point temperature, appliance & lighting use, and airflow behaviour were shown to be major estimators of total heating energy used over a year. Occupancy patterns were shown to be less significant factors. The regression model is limited to a single technical design and hence it would be useful, in future work, to examine how much the values of its coefficients change for other dwellings i.e. Passivhaus and other low-energy standards. However it is clear that in the case of the original Passivhaus terraces architectural and technical form, many of the concerns (including the author's) about the Passivhaus approach being overly sensitive to occupant behaviour and therefore not applicable in a diverse range of dwellings would appear to be unfounded.

Reflections

Since undertaking this project, work by Wilke *et al*. has used a similar approach to generate stochastic maps of occupant activities in a dwelling (Wilke, Haldi, Scartezzini, & Robinson, 2013). The methodology differs from the modified form of the Richardson tool adapted here, Wilke uses Time Use Survey data from France and a set of calibration methodologies to predict activity chains of occupants. Occupants are first treated as identical (as seen in Richardson's methodology) and then treated as more complex populations with a number of parameters which may affect behaviour (demographic parameters including age, income, health etc.). These demographic variables are of key importance – and highlight a gap in this work. To be able to estimate a number of variables about the demographics of the population of households, and apply this to customise the activity transition probabilities, one could greatly increase the usefulness of estimations and bridge the existing gap between technical and social research in this area. Further technical research in this area without developing sociological context is likely to miss many key conclusions, and be liable to flaws. It is the hope of the Author that projects such as Annex 66 will contribute to this important step which is too often missing in this area of research (IEA-EBC, 2013).

Future work would seek a method to integrate the techniques employed here within existing energy simulation software packages to assess the expected range of energy uses anticipated, based on a number of demographics. While academic applications of this methodology are limited, commercial applications of this method include informing more efficient sizing of local generation and storage capacity based on the heating and cooling loads required by buildings, and allow the design team to have a clearer picture of what ranges of energy a building is likely to achieve in-use, reducing any nasty surprises when conducting post-occupancy monitoring.

5.2 Case studies of occupant behaviour within social housing

Summary

As stated previously, a better understanding of occupant behaviour's impact on building energy use (and therefore a better understanding of the design-performance gap) is crucial to reduction of CO_2 emissions from the building stock, in line with UK Government targets. It is postulated that a better understanding of the determinants of occupant behaviour would be an interesting and useful study. Two sites in Exeter were identified for measurement – 21 social housing apartments in total, all achieving Passivhaus Certification. The circumstances of the project led to two phases of measurement, one before (or where not feasible, shortly after) occupation of the new apartments, and one after at least one full year of occupancy.

A survey was developed, with some sections underpinned by Azjen's Theory of Planned Behaviour (Ajzen et al., 1980) to assess the impact of attitudes and perceptions on behaviour. The rest of the survey questions regarded the demographics of the occupant, their current energy spend and perceived energy-related behaviours, and some questions of interest to Exeter City Council regarding satisfaction of expectations and use of communal spaces.

The survey was facilitated with occupants from a wide range of backgrounds and previous living situations, far wider than anticipated (i.e. elderly social tenants).

The response rate to the surveys, conducted via pre-arrangement and cold-calling, , was low, particularly over the second phase which began at least one year after initial occupation took place.

Anecdotal accounts of attitude change and behaviour were recorded, anonymised, and fed back to the Design Team (Gale and Snowden Architects and Exeter City Council Housing Team). Due to the low response rate a quantitative analysis was deemed to be non-robust, but is presented in this work.

Measurement of energy use by the Design Team was completed in 2014 in three of the 21 apartments, however measurements were not collected in any of the dwellings for which a complete survey dataset was collected, therefore no measurements were able to be linked to survey data. This was unforeseeable, however might have been overcome if better communication between the Design Team and researcher had

concluded in stipulation that surveys took place in the homes that were elected for measurements.

Reflections

Future work would include revisions to the behavioural & attitude survey, reducing the scope of data collected and relying more fully on proven techniques, for example all questions should be formatted as a Likert Scale - such a technique has been used with success by others and would be the starting point for future survey design.

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Appendix A – ApacheSim Calculation Overview

A review of the key physical principles are run through in the following sections, the bulk of which is sourced from the ApacheSim Calculation Methods (IES Limited, 2012), and is included for completeness and further understanding of the thermal simulation.

Heat conduction and storage

The diffusion of heat through surfaces is modelled by:

$$\boldsymbol{\nabla}.(\boldsymbol{\lambda\nabla T}) = \boldsymbol{\rho c}\frac{\boldsymbol{\delta T}}{\boldsymbol{\delta t}} \quad \textbf{(5.1)}$$

where λ is the conductivity ($\mathrm{m\,K\,W^{-1}}$) of the surface, T is the temperature (°C) at position x, y, z, and ρ is the material density ($kg\ m^{-3}$), and c is the specific heat capacity of the layer ($J\ K^{-1}\ kg^{-1}$). The air mass heat storage can be modelled as:

$$\boldsymbol{Q = \rho_a c_p V \frac{dT_a}{dt}}. \quad \textbf{(5.2)}$$

Assuming a uni-dimensional surface with constant λ, c_p, and ρ, (5.1) leads to:

$$\boldsymbol{\frac{d^2T}{dx^2} = \frac{\rho c}{\lambda}\frac{\delta T}{\delta t}} \quad \textbf{(5.3)}$$

where x is directed perpendicular to the surface element.

Because ApacheSim uses a finite difference approach for solving these heat transfer equations, the surface is discretised into nodes spaced by a local node spacing δ_n (m), and (5.3) becomes:

$$\boldsymbol{\frac{T_{n-1} - 2T + T_{n+1}}{{\delta_n}^2} = -\frac{\rho c}{\lambda}\frac{\delta T}{\delta t}} \quad \textbf{(5.4)}$$

where the node distribution distance is based on the Fourier number:

$$\boldsymbol{F = \frac{\lambda}{\rho c}\frac{\Delta t}{{\delta_n}^2}} \quad \textbf{(5.5)}$$

where Δt is the simulation time-step (s) defined by the user before a simulation. To discretise the time variable and solve the heat equation, ApacheSim uses alternating implicit (backward-difference) and explicit (forward-difference) methods:

$$\boldsymbol{\dot{T}_n^j = \frac{T_n^{j+1} - T_n^j}{\Delta t}} \quad \textbf{(5.6)}$$

and

$$\dot{T}_n^{j+1} = \frac{T_n^{j+1} - T_n^j}{\Delta t} \tag{5.7}$$

respectively, where T_n^j is the node temperature (°C) at time j and $\dot{T}_n^j$ is the time-derivative of temperature ($K\ s^{-1}$) at the node at time j.

Convective heat transfer

Both natural (buoyancy-driven) and forced (driven by external forces) convection types are modelled using linear approximations of the experimentally-derived equation $W = K(T_a - T_s)^n$, where W is the heat flux from the air to the surface, T_a is the bulk air temperature, T_s is the mean surface temperature, and K and n are coefficients. Forced convection of a sufficiently high velocity has $n = 1$ and thus the process is linear. Natural ventilation does exhibit more significant departures from $n = 1$, though ApacheSim does make a linear approximation, re-introducing non-linearity through admitting the constant to have non-linear terms, depending on the situation.

Exterior convection

According to wind-speed based measurements in a wind tunnel (McAdams, 1954),

$$h_c = 5.6 + 4.0v \qquad v < 4.88 \tag{5.8}$$

$$h_c = 7.2v^{0.78} \qquad v \geq 4.88 \tag{5.9}$$

where h_c is the convective heat transfer coefficient, and v is the wind speed ($m\ s^{-1}$) interpolated from the hourly record of wind speed in the weather file.

Interior convection

ApacheSim offers four methods for calculating the interior convection. These are:

1. CIBSE fixed convection coefficients, based on a constant (average) coefficient for internal surfaces: $\mathrm{h_c} = 3.0$

2. CIBSE variable convection coefficients, based on CIBSE Guide C's procedures for coefficients as a function of surface orientation: $\mathrm{h_c} = \mathrm{fC\Delta T^{n-1}}$ where f is the mean room air velocity, C is the surface orientation coefficient, and n is an exponent coefficient. See Guide C for the appropriate tables (CIBSE, 1986).

3. Alamdari-Hammond convection coefficients - an empirically established procedure for calculating convection coefficients applied within an iterative calculation procedure (Alamdari & Hammond, 1983).

4. User-specified fixed convection coefficients - input in the constructions dialogue.

The second method was selected for this simulation, as a compromise between accuracy and calculation time.

Heat transfer by air movement

Pre-specified air-exchanges i.e. infiltration, natural ventilation, or mechanical ventilation; and airflows calculated by MacroFlo are modelled in ApacheSim, all using a similar method:

$$\boldsymbol{Q = mc_p(T_i - T_a)}\,. \tag{5.10}$$

(5.10) gives the rate of heat transfer through a stream of air entering a space, where m is the air mass flow rate (kg s^{-1}), c_p is the specific heat capacity of air at constant pressure (J $kg^{-1}K^{-1}$), T_i is the supply temperature of the air, and T_a is the mean room air temperature (°C). This approach necessitates the assumption that the supply air temperature is equal to that of the room mean air temperature, in line with the homogenous model or 'stirred tank' assumption.

Water vapour gain associated with the air supply is calculated as:

$$\boldsymbol{w = m(g_i - g)} \tag{5.11}$$

where w is the water vapour gain ($kg\ s^{-1}$), g_i is the humidity ratio of the supply ($kg\ kg^{-1}$), and g is the humidity ratio in the room. Carbon dioxide gain is treated in a very similar way:

$$\boldsymbol{c = m(k_i - k)} \tag{5.12}$$

where c is the carbon dioxide gain ($ppm\ s^{-1}$), k_i is the carbon dioxide concentration of the supply (ppm), and k is the carbon dioxide concentration in the room.

Long-wave radiation (LWR) heat transfer

Jožef Stefan expressed the approximation of *grey*-body radiators to be:

$$\boldsymbol{dW = \frac{1}{\pi}\varepsilon\sigma\Theta^4\, cos(\theta)\, d\omega dA} \tag{5.13}$$

where W is the radiation power (W), ε is the surface emissivity ($W\ m^{-2}$), σ is the Stefan-Boltzmann constant ($5.6697 \times 10^{-8}\ W\ m^{-2}K^{-4}$), Θ is the absolute temperature of the surface (K), θ is the angle measured from the surface normal, $d\omega$

an element of solid angle, and dA an element of surface area (m^2). Integrating this over a solid angle gives the total radiation per unit area of a planar surface:

$$\boldsymbol{W = \varepsilon\sigma A\Theta^4} \,. \tag{5.14}$$

In addition to emitting LWR, surfaces also receive some power from sources around them, by Kirchhoff's Law this is a fraction of the total incident radiation is equal to the materials emissivity ε. ApacheSim takes both the emission and received radiation into account. This approach is somewhat simplified, as it assumes both perfect black-body emission and *Lambertian* reflectance, where the emission or reflectance of radiation is uniformly diffuse, i.e. the same flux no matter the angle-of-view.

The calculations are further simplified where it comes to interior radiation exchange between surfaces of objects. In theory, a model would be built which takes into account the radiation to and from each surface and every other surface within the solid angle of the surface plane (reciprocal radiant exchange areas). In reality, this calculation is quite intensive, and can be simplified by considering one surface which each other surface sees, rather than multiple, reducing the number of calculations from $0.5n^2$ to n, for n surfaces. The net radiant exchange between a surface and its surroundings in such models are generally of the form:

$$\boldsymbol{W = h_r(T_s - T_{MRT})} \tag{5.15}$$

where W is the net radiative loss of the surface (W), h_r is the surface heat transfer coefficient ($W\ W^{-1}$), T_s is the surface temperature (°C), and T_{MRT} is the mean radiant temperature of the enclosure (°C) (Carroll, 1981; Oppenhiem, 1956). Openings or 'holes' in the building model are attributed a solar transmittance and emissivity of 1, in effect creating a new diffusing medium into the opening which is considered in the calculations for adjacent spaces.

Air interaction with interior radiation exchange

The moisture in the air plays a significant role when modelling interior radiation exchange. Water vapour in the air can lead to a high air emissivity, dependent on mean path length, humidity, and pressure. CO_2 also plays a role in the air emissivity, about 2% of the total emissivity, though ApacheSim ignores this contribution.

Air emissivity has a large effect on the radiant temperature of a space by partially shielding warm surfaces, which can lead to reduced temperature perceived by the building occupants. In addition, the effect of air emissivity on humidity has a coupling effect on the interior radiant exchange; as the air emissivity rises, there is reduced surface-surface exchange and increased surface-air exchange, so due to the latent exchange, heat sources act as if their radiant fraction were reduced.

ApacheSim relies on Hottel and Cohen's radiant air exchange curve (Hottel & Cohen, 1958):

$$\boldsymbol{ln(\varepsilon_{air}) = -0.619 - (2.958 - 0.2184\, ln(p_w L_e))^2} \tag{5.16}$$

where p_w is the partial vapour pressure of the air (hP) and L_e is the mean free path length of the space (m), approximated to $L_e = 3.6\,V/A$. This equation is used by ApacheSim for the calculation of inter-surface radiant exchange, radiant exchange between surfaces and air, and distribution of any radiant gains in the room. Solar radiation is unaffected by the air emissivity, which is effectively transparent to short-wave radiation (SWR).

Exterior LWR

All external surfaces of a building are receiving and radiating an amount of LWR, and almost always a surface will radiate more than it absorbs. ApacheSim uses the European Solar Radiation Atlas (CEC, 1999) to model the net long-wave gain of surfaces. For external surfaces of inclination β (°):

$$\boldsymbol{L^*(\beta) = \varepsilon_e\left[L_{sky}(\beta) + L_g(\beta) - \sigma\Theta_e^4\right]} \tag{5.17}$$

where $L^*(\beta)$ is the net long-wave radiation gain ($W\,m^{-2}$), ε_e is the emissivity of the external surface ($W\,m^{-2}$), $L_{sky}(\beta)$ is the long-wave radiation received from the sky ($W\,m^{-2}$), $L_g(\beta)$ is the long-wave radiation received from the ground ($W\,m^{-2}$), and Θ_e is the absolute temperature of the external surface (K). For horizontal surfaces, the LWR received from the sky is estimated using a model of the atmospheric emissivity, with a modification for cloud cover:

$$\boldsymbol{L_{sky}(0) = \sigma\Theta_a^4\left[0.904 - \left(0.304 - 0.061p_w^{0.5}\right)(1-c) - 0.005p_w^{0.5}\right]} \tag{5.18}$$

where Θ_a is the external absolute air temperature (°C), p_w is the external air water vapour pressure ($hectopascal, hPa$), and c is cloud cover fraction.

$$\boldsymbol{L_{sky}(\beta) = L_{sky}(0)F_{sky} + 0.09k_3(\beta)\{1 - c[0.7067 + 0.00822T_a]\}\sigma\Theta_a^4} \tag{5.19}$$

where the shape factor from the surface to the sky is $F_{sky} = \cos^2(0.5\beta)$, T_a is the external air temperature (°C), and:

$$k_3(\boldsymbol{\beta}) = \mathbf{0.7629}(.\mathbf{01}\boldsymbol{\beta}')^4 - \mathbf{2.2215}(.\mathbf{01}\boldsymbol{\beta}')^3 + \mathbf{1.7483}(.\mathbf{01}\boldsymbol{\beta}')^2 + \mathbf{0.054}(.\mathbf{01}\boldsymbol{\beta}') \quad \textbf{(5.20)}$$

where for inclined ($\beta \leq 90°$) surfaces $\beta' = \beta$ and for over-hanging ($\beta > 90°$) surfaces $\beta' = 180 - \beta$, avoiding non-physical behaviour.

Finally, the LWR received from the ground in (5.17) is calculated by:

$$L_g(\boldsymbol{\beta}) = \boldsymbol{\sigma}\{\mathbf{0.980}\boldsymbol{\Theta}_a + \mathbf{0.37}(\mathbf{1} - \boldsymbol{\rho}_g)\boldsymbol{I}_{glob}\}^4 \boldsymbol{F}_{gnd} \quad \textbf{(5.21)}$$

where ρ_g is the short-wave ground reflectance (albedo), I_{glob} is the solar flux on the horizontal plane ($W\,m^{-2}$), and the shape factor from the surface to the ground $F_{gnd} = 1 - F_{sky} = sin^2(0.5\beta)$. Any shading factors from the SunCast model or construction local shading devices are taken into account through a modification of the sky and ground shape factors by the shading factor f_{shd}, where the radiosity of the shading objects are equal to that of the ground.

Solar radiation

Received SWR from the sun is treated as three components:

(1) Direct solar radiation from the sun's disc, I_{dir} (from weather file)

(2) Diffuse radiation from the sky measured on the horizontal plane, I_{hdiff} (from weather file)

(3) Diffuse radiation scattered by the ground and any local shading (from SunCast (Wm^{-2}))

The direct solar flux is perhaps the easiest to calculate, where I_{dir} is the direct solar flux incident of a surface (Wm^{-2}), I_{beam} is the solar flux measured perpendicular to the beam (Wm^{-2}), and θ is the angle of incidence in degrees:

$$\boldsymbol{I}_{dir} = \boldsymbol{I}_{beam}\boldsymbol{cos}(\boldsymbol{\theta})\,. \quad \textbf{(5.22)}$$

The diffuse solar flux has components from the sky I_{sdif} (Wm^{-2}) and the ground I_{gdif} (Wm^{-2}):

$$\boldsymbol{I}_{sdif} = \boldsymbol{I}_{hdif}\boldsymbol{cos}^2(\mathbf{0.5}\boldsymbol{\beta}) \quad \textbf{(5.23)}$$

$$\boldsymbol{I}_{gdif} = \boldsymbol{\rho}_g\boldsymbol{I}_{hglob}\boldsymbol{sin}^2(\mathbf{0.5}\boldsymbol{\beta}) \quad \textbf{(5.24)}$$

where the total solar flux on the horizontal plane $I_{hglob} = I_{hdif} + I_{beam}\sin(\alpha)$, ($\alpha$ is the solar altitude).

This method assumes an isotropic diffuse radiation from the sky. The anisotropic calculation option uses a 'circumsolar radiation' method to model the diffuse radiation from the sky, based on work by John Hay and others (Hay, 1993; Perez, Scott, & Stewart, 1983). Therefore (5.23) is replaced with:

$$\boldsymbol{I_{sdif} = I_{hdif}\left[\kappa\frac{cos(\theta)}{cos(90° - \alpha)} + 0.5(1 - \kappa)(1 + cos(\beta))\right]} \tag{5.25}$$

where κ is the ratio of solar radiation on the surface to radiation on a horizontal plane.

Appendix B – Peer-Reviewed Journal Publication

This paper has been removed due to copyright concerns.

The paper in question is:

Thomas S. Blight, David A. Coley, Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings, Energy and Buildings, Volume 66, November 2013, Pages 183-192, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2013.06.030.

It can be found here: http://www.sciencedirect.com/science/article/pii/S0378778813003794

Appendix C – Phase 1 Survey

Survey Reference:

UNIVERSITY OF EXETER
Centre for Energy and the Environment

Centre for Energy and the Environment
University of Exeter
Pre-occupancy Survey

Contact: Tom Blight
PhD Student – Low Energy Building Design
t.s.blight@exeter.ac.uk
01392 724145

This survey is a part of a study on change in behaviour and attitude over a house-move to a low-energy home. The study takes the form of three householder interviews/surveys at different points during the move to a new environment, combined with monitoring the performance of the low-energy building via energy and climate data collected on-site. This project is supervised by Dr Joanne Smith at the School of Psychology, University of Exeter.

This study has been approved by the School Of Psychology Research Ethics Committee, University Of Exeter. Data collected in this study will be treated in accordance with the Data Protection Act, and will only be shared in anonymous compiled form. You have the right to cancel your involvement with the study at any time.

This survey has been conducted with both householders present?

True / False

This survey has been conducted with a researcher present?

True / False

Consent to involvement:

SIGNED ______________________________ **DATE** _____________________

Thank you for your participation.

Section 1 – About Your Property

1. Type of Property

☐ Terrace ☐ Detached ☐ Flat

☐ End-of-terrace ☐ Semi-detached Other …………………

2. When was your property built (approximately)?

☐ Pre-1880 ☐ 1920-1960 ☐ Post-1980

☐ 1880-1920 ☐ 1960-1980 ☐ Unsure

3. How many bedrooms does your house have? ……………

4. Do you have a loft conversion? ……………

5. Are there any notable extensions/modifications to the property?

……

……

6. Please select the most appropriate descriptions of the windows in your home:

a. Glazing:

☐ Single Glazing
☐ Double Glazing
☐ Triple Glazing

b. Frames:

☐ Metal Frames
☐ Wooden Frames
☐ PVC Frames

7. Please identify the flooring type in your home:

a. Flooring:

☐ Mainly fixed carpet
☐ Even mix carpet & hard surfaces
☐ Mainly hard surfaces

b. Rugs:

☐ No additional rugs/mats
☐ Some rooms additional rugs/mats
☐ Most rooms additional rugs/mats

THE FOLLOWING QUESTIONS ARE ABOUT THE SPACE HEATING AND COOLING SYSTEMS IN YOUR HOME

8. What fuel type does your space heating use?

☐ Electric
☐ Wood
☐ Gas
☐ Coal/Coal derivative

(If mixture, please describe) …………………………………………………………………………..

……

9. Please pick the best description of your heating system from the options below, or describe:

☐ Central heating with conventional radiators
☐ Solid fuel heating - Wood
☐ Storage heaters
☐ Solid fuel heating - Coal
☐ Portable electric heaters

Other/mix (please describe): ……………………………………………………………………..

10. What type of cooling system in do you employ in your home?

☐ Air conditioning (fixed unit)
☐ Air conditioning (portable unit)
☐ Ceiling fans
☐ Portable fans
☐ None / natural cooling (windows/grilles/vents)
☐ Other…………………..

11. How do you pay for energy?

☐ Contractual agreement
☐ Pay As You Go
☐ Coin-Operated Meter
☐ Other ……………………………

12. Do you receive financial support to cover part of your fuel costs? Y / N

THE FOLLOWING QUESTIONS ARE ABOUT YOUR USE OF HEATING AND COOLING CONTROLS

13. In an average year, which months of the year do you use a heating system?

Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	

(Please mark boxes)

14. Does the heating system use a thermostat? (If **no**, please skip to **Question 18.**)
Y / N

15. Does the heating thermostat use an automated timer?
Y / N

16. During the heating season what range will you generally use on your heating thermostat throughout the day (please indicate temperatures in boxes)?

	Midnight - 02:00	02:00 - 04:00	04:00 - 06:00	06:00 - 08:00	08:00 - 10:00	10:00 -Midday	Midday - 14:00	14:00 - 16:00	16:00 - 18:00	18:00 - 20:00	20:00 - 22:00	22:00 Midnight
Weekdays												
Weekends												

EXAMPLE:

Midnight - 02:00	02:00 - 04:00	04:00 - 06:00	06:00 - 08:00	08:00 - 10:00	10:00 -Midday	Midday - 14:00	14:00 - 16:00	16:00 - 18:00	18:00 - 20:00	20:00 - 22:00	22:00 - Midnight
OFF			18 °C						22 °C		OFF

17. Please indicate which setting you keep radiators / heaters on during the heating season.

	high	*med*	*low*	*off*		*high*	*med*	*low*	*off*
a. Bathrooms	☐	☐	☐	☐	d. Lounge	☐	☐	☐	☐
b. Main Bedrm	☐	☐	☐	☐	e. Kitchen	☐	☐	☐	☐
c. Other Beds	☐	☐	☐	☐	f. Hall	☐	☐	☐	☐

18. How do you feel about the usability of your current heating controls?

1	2	3	4	5
difficult-to-use	•	satisfactory	•	easy-to-use

Comments

………

………

19. Approximately, how much do you spend on the fuel stated in Question 8 in an average month over the heating season?

☐ £0-29 ☐ £60-89 ☐ £120-149

☐ £30-59 ☐ £90-119 ☐ £150 or over

a. Would you mind if we have a copy of your energy bills? Y / N

20. In an average year, which months of the year do you use a cooling system?

Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	

(Please mark boxes)

21. Does your cooling system use a thermostat? (If **no**, please skip to **Question 24.**)

☐ Yes ☐ No

22. Does the thermostat use an automated timer?

☐ Yes ☐ No

23. During the cooling season what range will you generally use on your cooling thermostat throughout the day (please indicate temperatures in boxes)?

	Midnight - 02:00		02:00 - 04:00		04:00 - 06:00		06:00 - 08:00		08:00 - 10:00		10:00 -Midday		Midday - 14:00		14:00 - 16:00		16:00 - 18:00		18:00 - 20:00		20:00 - 22:00		22:00 Midnight	
Weekdays																								
Weekends																								

EXAMPLE:

Midnight - 02:00		02:00 - 04:00		04:00 - 06:00		06:00 - 08:00		08:00 - 10:00		10:00 -Midday		Midday - 14:00		14:00 - 16:00		16:00 - 18:00		18:00 - 20:00		20:00 - 22:00		22:00 Midnight	
OFF →						20 °C →													22 °C →			OFF	

THE FOLLOWING QUESTIONS ARE ABOUT YOUR USE OF WINDOWS AND BLINDS

24. During the heating season, in which rooms do you regularly open windows? (select all that apply)

a. ☐ Bathrooms
b. ☐ Main bedroom
c. ☐ Other bedrooms
d. ☐ Lounge
e. ☐ Kitchen
f. ☐ Hall

25. During the heating season, under what conditions would you normally open windows? (select all that apply)

☐ When hot
☐ When musty / dank
☐ Moisture control - Cooking
☐ Moisture control – Washing
☐ Other moisture control
☐ Aid dying of clothes
☐ When children/pets outdoors
☐ Any conditions – prefer a breeze
☐ When going to sleep
Other ……………………………..

26. Under what conditions would you normally close curtains/blinds? (select all that apply)

☐ Night time - privacy
☐ General Sun-shading
☐ Sun-shading - using TV/PC screen
☐ Leaving the house for a period
☐ Warmer outside than inside
☐ Warmer inside than outside
☐ Help stop cold draughts
☐ Other ……………………………..

THE FOLLOWING QUESTIONS RELATE TO THE AIR QUALITY IN YOUR HOME

27. Do you have problems with damp/mould growth…

a. …in summer months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

b. …in winter months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

c. Do you take any precautions to control damp/mould growth?

………

………

………

28. Do you notice odours inside your home…

a. …in summer months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

b. …in winter months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

c. Do you take any precautions to control odours?

………

………

………

29. Please tick all the odour types that apply:

☐ Chemical odours/fumes
☐ Musty/dank odours
☐ Bacterial odours
☐ Combustion of heating/cooking fuel
☐ Tobacco smoke
Other …………………………..

30. Do you have any specific concerns about the indoor air quality in your home?

………

………

………

THE FOLLOWING QUESTIONS ARE ABOUT MOISTURE LEVELS WHICH ARE RELATED TO YOUR COOKING, BATHING, AND DRYING BEHAVIOUR

31. Do you have an extractor fan in the kitchen?

☐ Yes ☐ No

a. If yes: when do you use the extractor fan in the kitchen?

☐ Always when cooking
☐ When cooking smelly foods
☐ **After** cooking
☐ If something has burnt
☐ Never
Other ………………………….

32. Do you mainly use a bath or a shower to wash?

☐ Bath
☐ Shower

33. How many times in the average week do you take a bath or a shower? ………

34. If you shower, for how long – typically – is the water running? ………

35. Do you have an extractor fan in the bathroom?

☐ Yes
☐ No

a. If yes: when do you use the extractor fan in the bathroom?

☐ Always
☐ When bathroom occupied
☐ Never
☐ **As** I shower or bath
☐ **After** I shower or bath
Other ………………………….

36. Where do you usually dry your washing? (select **all** that apply)

☐ Inside house (e.g. lounge, kitchen, bathroom, etc.)
☐ Inside area attached to house (e.g. lean-to, garage, conservatory, etc.)
☐ Outside drying where possible
☐ Tumble dryer
☐ Washing machine dryer
☐ Radiator drying rack
Other ………………………….

37. Do you keep any household plants within your home?

☐ 0
☐ 1-3
☐ 4-6
☐ 7-10
☐ 11-20
☐ 20+

THE FOLLOWING QUESTIONS ARE ABOUT YOUR USE OF OUTDOOR SPACES

38. Do you have access to a garden/allotment in your current residence?

☐ Yes ☐ No

a. If yes, which of the following describe your uses of the space?

Aesthetic

☐ Ornamental gardening

☐ Landscape gardening

Recreational

☐ Used by children

☐ Arts/Crafts

☐ Eating meals

☐ Social events

☐ Bird-watching

Functional

☐ Vegetable gardening

☐ Herb gardening

☐ Storage

☐ Engineering / Maintenance Tasks

☐ Used by pets

Other ……………………………………………

……………………………………………………………

b. How regularly are you in your garden for the uses specified above?

Summer time

☐ Daily

☐ 4-6 times per week

☐ 2-3 times per week

☐ Weekly

☐ Monthly

☐ Less than once per month

Winter time

☐ Daily

☐ 4-6 times per week

☐ 2-3 times per week

☐ Weekly

☐ Monthly

☐ Less than once per month

39. Do you supplement your diet with food you have grown / foraged from your garden or elsewhere?

☐ Yes ☐ No

a. If yes, please give details:

………

………

………

THE FOLLOWING QUESTIONS RELATE TO YOUR PERSONAL EXPECTATIONS OF THE NEW DWELLING ENVIRONMENT

40. How important a driver was the PassivHaus certification of your new home in deciding to move?

1	2	3	4	5
not important / indifferent	•	•	•	very important

41. Had you heard of the PassivHaus certification before this development began?

☐ Yes ☐ No

a. If yes: where did you first hear about the PassivHaus certification?

…………………………………………………………………………………………

42. How do you expect the thermal environment in a PassivHaus will compare with that of your current dwelling?

1	2	3	4	5
less comfortable	•	no change	•	more comfortable

43. How do you expect the air quality of your new dwelling will compare to your current dwelling?

1	2	3	4	5
lesser quality	•	no change	•	better quality

44. How do you expect the energy costs will compare with your current dwelling?

1	2	3	4	5
less affordable	•	no change	•	more affordable

45. How do you expect the ease of use of heating and cooling systems to compare to your current dwelling?

1	2	3	4	5
less comfortable	•	no change	•	more comfortable

PLEASE TURN OVER FOR SECTION 2 ⟶

Section 2 – Wider Behaviour

Ecological Behaviour

46. How often have you done each of the following in the past year (circle):

a. Looked for ways to reuse things

1	2	3	4	5
never	rarely	sometimes	often	very often

b. Recycled all possible products (e.g. newspapers, cans, bottles)

1	2	3	4	5
never	rarely	sometimes	often	very often

c. Picked up litter that was not your own.

1	2	3	4	5
never	rarely	sometimes	often	very often

d. Composted food scraps.

1	2	3	4	5
never	rarely	sometimes	often	very often

e. Conserved petrol by walking, using public transport, or bicycling.

1	2	3	4	5
never	rarely	sometimes	often	very often

f. Wrote a letter supporting an environmental issue.

1	2	3	4	5
never	rarely	sometimes	often	very often

g. Replaced traditional light bulbs with energy efficient light bulbs

1	2	3	4	5
never	rarely	sometimes	often	very often

h. Replaced old appliances with more energy efficient appliances

1	2	3	4	5
never	rarely	sometimes	often	very often

i. Turned down the heating

1	2	3	4	5
never	rarely	sometimes	often	very often

j. Switched appliances off completely (rather than leaving them on standby)

1	2	3	4	5
never	rarely	sometimes	often	very often

Attitudes towards climate change

47. Please indicate your agreement with the following statements (circle):

a. I worry about the effect that humans are having on the Earth's climate.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

b. I am concerned about the impact that human-induced climate change might have on future generations.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

c. The British government should be implementing immediate measures to drastically reduce carbon emissions.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

d. Britain should not consider taking any action to reduce carbon emissions until other nations around the world make similar commitments.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

e. I feel a sense of responsibility to reduce my own personal carbon emissions.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

Your energy behaviour

48. Please indicate which best represents your answer to the following questions (circle):

a. How often do you try to conserve energy?

1	2	3	4	5
never	rarely	sometimes	frequently	almost always

In deciding to conserve energy, how important is it to you…

b. ..that using less energy saves money

1	2	3	4	5
not at all important	•	•	•	extremely important

c. ..that using less energy protects the environment

1	2	3	4	5
not at all important	•	•	•	extremely important

d. ..that using less energy benefits society

1	2	3	4	5
not at all important	•	•	•	extremely important

e. ..that a lot of other people are trying to conserve energy

1	2	3	4	5
not at all important	•	•	•	extremely important

f. How often do you think that other people around you (e.g., friends, neighbours, family) try to conserve energy?

1	2	3	4	5
never	rarely	sometimes	frequently	almost always

g. How much do you think that other people around you (e.g., friends, neighbours, family) approve of trying to conserve energy?

1	2	3	4	5
not at all	•	•	•	very much

Section 3 – The Household

49. Please indicate the number of persons:

a. Working full-time ___
b. Working part-time ___
c. Studying ___
d. Looking after house/children ___
e. Retired ___
f. Unemployed ___
g. Disabled ___

If you answered **g:** please indicate the nature of the disability/disabilities:

………

50. Please indicate the level of education achieved in your household by each person:

☐ No formal qualifications
☐ GCSE/O-Level/CSE
☐ Vocational qualification
☐ A-Level or equivalent
☐ Bachelor Degree or equivalent
☐ Masters/PhD or equivalent
☐ Still Studying
Other ……………………………..

51. What is the approximate annual income bracket of the household?

☐ £0 - £5,000
☐ £5,000 - £10,000
☐ £10,000 - £15,000
☐ £15,000 - £20,000
☐ £20,000 - £30,000
☐ £30,000 - £40,000
☐ £40,000 - £50,000
☐ £50,000 or above

52. What are usual times people are in the house:

a) …on a weekday?

	6:00			9:00			12:00			15:00			18:00			21:00			0:00			3:00		
Person 1																								
Person 2																								
Guest																								

b) …on a weekend?

	6:00			9:00			12:00			15:00			18:00			21:00			0:00			3:00		
Person 1																								
Person 2																								
Guest																								

(Please shade occupied hours)

THE FOLLOWING QUESTIONS ARE ON THE EXISTING HEALTH OF THE HOUSEHOLD IN TERMS OF RESPIRATORY CONDITIONS

53. Does anybody in the household suffer from any of the following respiratory conditions?

☐ Asthma

☐ Hay fever

☐ Other respiratory conditions ………………………………..

a. If yes, please comment on the *duration* of the condition(s) and on any *current treatments* and any *past treatments* you have used.

………

………

………

54. Does anybody in the household suffer from the following skin conditions?

☐ Eczema

☐ Dermatitis

☐ Dandruff

Other ……………………………

a. If yes, please comment on the *duration* of the condition(s) and on any *current treatments* and any *past treatments* you have used.

………

………

………

END OF SURVEY

Thank you, your time is appreciated.

Appendix D – Phase 2 Survey

Rowan House & Knights Place
Post-occupancy Survey

Contact: Tom Blight
PhD Student – Low Energy Building Design
t.s.blight@bath.ac.uk

This survey is a part two of a study on change in behaviour and attitude over a house-move to a low-energy home. The study takes the form of two householder interviews/surveys at different points during the move to a new environment, combined with monitoring the performance of the low-energy building via energy and climate data collected on-site. This project is supervised by Dr Joanne Smith at the School of Psychology, University of Exeter.

This study has been approved by the School Of Psychology Research Ethics Committee, University Of Exeter. Data collected in this study will be treated in accordance with the Data Protection Act, and will only be shared in anonymous compiled form. You have the right to cancel your involvement with the study at any time.

This survey has been conducted with both householders present?
True / False

This survey has been conducted with a researcher present?
True / False

Date

D	D	M	M	Y	Y

Thank you for your participation.

1. **Please rate the comfort in your house on the scale below-**

   a. **In very cold weather**

1	2	3	4	5	6	7
.	.	.	.	.	.	.
very cold	cold	cool	comfortable	warm	hot	very hot

   b. **In very warm weather**

1	2	3	4	5	6	7
.	.	.	.	.	.	.
very cold	cold	cool	comfortable	warm	hot	very hot

   c. **In general**

1	2	3	4	5	6	7
.	.	.	.	.	.	.
very cold	cold	cool	comfortable	warm	hot	very hot

2. **How have you found the thermal environment in a PassivHaus compares with that of your previous dwelling?**

1	2	3	4	5
.	.	.	.	.
less comfortable		indifferent		more comfortable

3. **How have you found the air quality of your new dwelling compares to your previous dwelling?**

1	2	3	4	5
.	.	.	.	.
less quality		indifferent		more quality

4. **How have you found the energy costs differ compared with your previous dwelling?**

1	2	3	4	5
.	.	.	.	.
less affordable		indifferent		more affordable

5. **How do you feel about the usability of your heating controls compared to your previous dwelling?**

1	2	3	4	5
.	.	.	.	.
less easy		indifferent		more easy

Comments

……

……

6. Do you feel that you've had control over the thermal environment?

1	2	3	4	5
.	.	.	.	.
no control		some		full control

7. Are you confident that you can change the environment to suit your preferences?

1	2	3	4	5
.	.	.	.	.
no confidence		some		full confidence

8. Is there anything you find *confusing* about the heating/ventilation controls?

………

………

…………………………………………………………………………………………………

9. Is there anything you find *irritating* about the heating/ventilation controls?

………

………

…………………………………………………………………………………………………

10. During the heating season what range will you generally use on your heating thermostat throughout the day (please indicate temperatures in boxes)?

	Midnight - 02:00		02:00 - 04:00		04:00 - 06:00		06:00 - 08:00		08:00 - 10:00		10:00 -Midday		Midday - 14:00		14:00 - 16:00		16:00 - 18:00		18:00 - 20:00		20:00 - 22:00		22:00 Midnight	
Weekdays																								
Weekends																								

EXAMPLE:

Midnight - 02:00		02:00 - 04:00		04:00 - 06:00		06:00 - 08:00		08:00 - 10:00		10:00 -Midday		Midday - 14:00		14:00 - 16:00		16:00 - 18:00		18:00 - 20:00		20:00 - 22:00		22:00 - Midnight	
OFF						18 °C													22 °C			OFF	

11. Did you feel you were adequately acquainted with the use of the systems by the council / experts?

………
………
……………………………………………………………………………………………………..

12. Were there any problems in the initial weeks/months of living in the property?

………
………
……………………………………………………………………………………………………..

13. Were there any problems in the initial months/weeks of the heating season?

………
………
……………………………………………………………………………………………………..

THE FOLLOWING QUESTIONS ARE ABOUT YOUR USE OF WINDOWS AND BLINDS

14. During the heating season, in which rooms do you regularly open windows? (select all that apply)

a. ☐ Bathrooms
b. ☐ Main bedroom
c. ☐ Other bedrooms
d. ☐ Lounge
e. ☐ Kitchen
f. ☐ Hall

15. During the heating season, under what conditions would you normally open windows? (select all that apply)

☐ When hot
☐ When musty / dank
☐ Moisture control - Cooking
☐ Moisture control – Washing
☐ Other moisture control
☐ Aid dying of clothes
☐ When children/pets outdoors
☐ Any conditions – prefer a breeze
☐ When going to sleep
Other …………………………..

16. During summer, under what conditions would you normally open windows? (select all that apply)

☐ When hot
☐ When musty / dank
☐ Moisture control - Cooking
☐ Moisture control – Washing

 Other moisture control
 Aid dying of clothes
 When children/pets outdoors
 Any conditions – prefer a breeze
 When going to sleep
Other ……………………………..

17. Under what conditions would you normally close curtains/blinds? (select all that apply)

 Night time - privacy
 General Sun-shading
 Sun-shading - using TV/PC screen
 Leaving the house for a period
 Warmer outside than inside
 Warmer inside than outside
 Help stop cold draughts
 Other ……………………………..

THE FOLLOWING QUESTIONS ARE ABOUT MOISTURE LEVELS WHICH ARE RELATED TO YOUR COOKING, BATHING, AND DRYING BEHAVIOUR

18. When do you use the extractor fan in the kitchen?

 Always when cooking
 When cooking smelly foods
 After cooking
 If something has burnt
 Never
Other …………………………

19. How many times in the average week do you take a shower? ………

a. For how long – typically – is the water running? ………

20. When do you use the extractor fan in the bathroom?

 Always
 When bathroom occupied
 Never
 As I shower or bath
 After I shower or bath
Other …………………………

21. Where do you usually dry your washing? (select **all** that apply)

 Inside house (e.g. lounge, kitchen, bathroom, etc.)
 Outside drying where possible
 Tumble dryer
 Washing machine dryer
 Radiator drying rack
Other …………………………

22. Do you keep any household plants within your home?

☐ 0
☐ 1-3
☐ 4-6
☐ 7-10
☐ 11-20
☐ 20+

THE FOLLOWING QUESTIONS ARE ABOUT YOUR USE OF OUTDOOR SPACES

23. Do you have access to a garden/allotment in your current residence?

☐ Yes ☐ No

a. If yes, which of the following describe your uses of the space?

Aesthetic

☐ Ornamental gardening

☐ Landscape gardening

Recreational

☐ Used by children

☐ Arts/Crafts

☐ Eating meals

☐ Social events

☐ Bird-watching

Functional

☐ Vegetable gardening

☐ Herb gardening

☐ Storage

☐ Engineering / Maintenance Tasks

☐ Used by pets

Other ………………………………………..

……………………………………………………………

b. How regularly are you in your garden for the uses specified above?

Summer time

☐ Daily

☐ 4-6 times per week

☐ 2-3 times per week

☐ Weekly

☐ Monthly

☐ Less than once per month

Winter time

☐ Daily

☐ 4-6 times per week

☐ 2-3 times per week

☐ Weekly

☐ Monthly

☐ Less than once per month

24. Do you supplement your diet with food you have grown / foraged from your garden or elsewhere?

☐ Yes ☐ No

a. If yes, please give details:

………

………

………

25. Do you receive financial support to cover part of your fuel costs? Y / N

26. Approximately, how much do you spend on energy in an average month over the heating season?

☐ £0-29	☐ £60-89	☐ £120-149
☐ £30-59	☐ £90-119	☐ £150 or over

Exact figure if available ________

a. Would you mind if we have a copy of your energy bills? Y / N=

27. Have you have problems with damp/mould growth…

a. …in summer months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

b. …in winter months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

c. Do you take any precautions to control damp/mould growth?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

28. Have you noticed odours inside your home…

a. …in summer months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

b. …in winter months?

1	2	3	4	5
not at all	•	on occasion	•	consistently

c. Do you take any precautions to control odours?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

29. Please tick all the odour types that apply:

- ☐ Chemical odours/fumes
- ☐ Musty/dank odours
- ☐ Bacterial odours
- ☐ Combustion of heating/cooking fuel
- ☐ Tobacco smoke
- Other …………………………..

30. Do you have any specific concerns about the indoor air quality in your home?

……

……

……

Section 2 – Wider Behaviour

Ecological Behaviour

31. How often have you done each of the following in the past year (circle):

a. Looked for ways to reuse things

1	2	3	4	5
never	rarely	sometimes	often	very often

b. Recycled all possible products (e.g. newspapers, cans, bottles)

1	2	3	4	5
never	rarely	sometimes	often	very often

c. Picked up litter that was not your own.

1	2	3	4	5
never	rarely	sometimes	often	very often

d. Composted food scraps.

1	2	3	4	5
never	rarely	sometimes	often	very often

e. Conserved petrol by walking, using public transport, or bicycling.

1	2	3	4	5
never	rarely	sometimes	often	very often

f. Wrote a letter supporting an environmental issue.

1	2	3	4	5
never	rarely	sometimes	often	very often

g. Replaced traditional light bulbs with energy efficient light bulbs

1	2	3	4	5
never	rarely	sometimes	often	very often

h. Replaced old appliances with more energy efficient appliances

1	2	3	4	5
never	rarely	sometimes	often	very often

i. Turned down the heating

1	2	3	4	5
never	rarely	sometimes	often	very often

j. Switched appliances off completely (rather than leaving them on standby)

1	2	3	4	5
never	rarely	sometimes	often	very often

Attitudes towards climate change

32. Please indicate your agreement with the following statements (circle):

a. I worry about the effect that humans are having on the Earth's climate.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

b. I am concerned about the impact that human-induced climate change might have on future generations.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

c. The British government should be implementing immediate measures to drastically reduce carbon emissions.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

d. Britain should not consider taking any action to reduce carbon emissions until other nations around the world make similar commitments.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

e. I feel a sense of responsibility to reduce my own personal carbon emissions.

1	2	3	4	5
strongly disagree	•	•	•	strongly agree

Your energy behaviour

33. Please indicate which best represents your answer to the following questions (circle):

a. How often do you try to conserve energy?

1	2	3	4	5
never	rarely	sometimes	frequently	almost always

In deciding to conserve energy, how important is it to you…

b. ..that using less energy saves money

1	2	3	4	5
not at all important	•	•	•	extremely important

c. ..that using less energy protects the environment

1	2	3	4	5
not at all important	•	•	•	extremely important

d. ..that using less energy benefits society

1	2	3	4	5
not at all important	•	•	•	extremely important

e. ..that a lot of other people are trying to conserve energy

1	2	3	4	5
not at all important	•	•	•	extremely important

f. How often do you think that other people around you (e.g., friends, neighbours, family) try to conserve energy?

1	2	3	4	5
never	rarely	sometimes	frequently	almost always

g. How much do you think that other people around you (e.g., friends, neighbours, family) approve of trying to conserve energy?

1	2	3	4	5
not at all	•	•	•	very much

34. How do you feel about the PassivHaus certification in terms of general environmental comfort?

1	2	3	4	5
.	.	.	.	.
negative		**indifferent**		**positive**

35. Would you recommend living in a PassivHaus to family / friends?

1	2	3	4	5

.	.	.	.	.
very unlikely		**indifferent**		**very likely**

a. Why?

....

36. Do you think living in a PassivHaus is suited to the British people in general?

1	2	3	4	5
.	.	.	.	.
very unlikely		**indifferent**		**very likely**

a. Why?

....

Section 3 – The Household

37. When did you move into your current home?

D	D	M	M	Y	Y

38. Please indicate the number of persons:

a. Working full-time ___
b. Working part-time ___
c. Studying ___
d. Looking after house/children ___
e. Retired ___
f. Unemployed ___
g. Disabled ___

If you answered **g:** please indicate the nature of the disability/disabilities:

....

39. What is the approximate annual income bracket of the household?

☐ £0 - £5,000
☐ £5,000 - £10,000
☐ £10,000 - £15,000
☐ £15,000 - £20,000
☐ £20,000 - £30,000
☐ £30,000 - £40,000
☐ £40,000 - £50,000
☐ £50,000 or above

40. What are usual times people are in the house:

a) ...on a weekday?

	6:00			9:00			12:00			15:00			18:00			21:00			0:00			3:00		
Person 1 Person 2 Guest																								

b) ...on a weekend?

	6:00			9:00			12:00			15:00			18:00			21:00			0:00			3:00		
Person 1																								
Person 2																								
Guest																								

(Please shade occupied hours)

THE FOLLOWING QUESTIONS ARE ON THE EXISTING HEALTH OF THE HOUSEHOLD IN TERMS OF RESPIRATORY CONDITIONS

41. Does anybody in the household suffer from any of the following respiratory conditions?

☐ Asthma

☐ Hay fever

☐ Other respiratory conditions

………………………………..

a. If yes, please comment on the *duration* of the condition(s) and on any *current treatments* and any *past treatments* you have used.

………………………………………………………………………………………………………

………………………………………………………………………………………………………

………………………………………………………………………………………………………

b. Please comment on any change in the condition/s since moving into your new home.

………………………………………………………………………………………………………

………………………………………………………………………………………………………

………………………………………………………………………………………………………

42. Does anybody in the household suffer from the following skin conditions?

☐ Eczema

☐ Dermatitis

☐ Dandruff

Other ……………………….

a. If yes, please comment on the *duration* of the condition(s) and on any *current treatments* and any *past treatments* you have used.

………

………

………

a. Please comment on any change in the condition/s since moving into your new home.

………

………

………

END OF SURVEY

Thank you, your time is appreciated.